Argonne NATIONAL LABORATORY

MPI for Scalable Computing (continued from yesterday)

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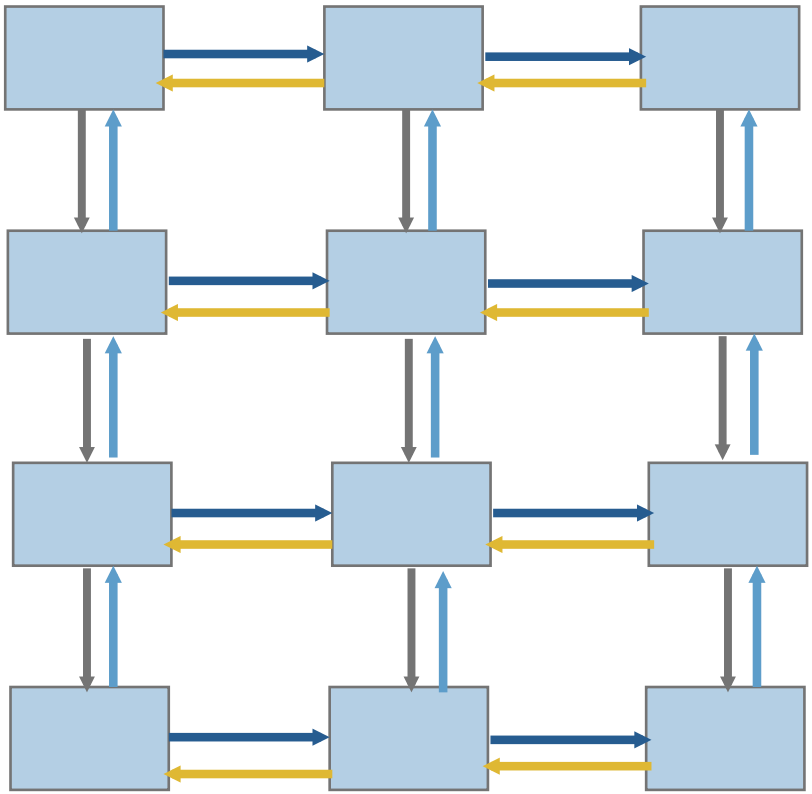
Costs of Unintended Synchronization

Unexpected Hot Spots

- Even simple operations can give surprising performance behavior.
- Examples arise even in common grid exchange patterns
- Message passing illustrates problems present even in shared memory
  - Blocking operations may cause unavoidable stalls

Mesh Exchange

- Exchange data on a mesh



Sample Code

- Do i=1,n_neighbors

  Call MPI_Send(edge(1,i), len, MPI_REAL,&

  nbr(i), tag,comm, ierr)

  Enddo

  Do i=1,n_neighbors

  Call MPI_Recv(edge(1,i), len, MPI_REAL,&

  nbr(i), tag, comm, status, ierr)

  Enddo

Deadlocks!

- All of the sends may block, waiting for a matching receive (will for large enough messages)
- The variation of

```
if (has down nbr) then
   Call MPI_Send( … down … )
endif
if (has up nbr) then
   Call MPI_Recv( … up … )
endif
…
```

sequentializes (all except the bottom process blocks)

Sequentialization

Start Send	Start Send	Start Send	Start Send	Start Send	Start Send Send	Send Recv	Recv
				Send	Recv		
			Send	Recv			
		Send	Recv				
	Send	Recv					
Send	Recv						

Fix 1: Use Irecv

- Do i=1,n_neighbors

  Call MPI_Irecv(inedge(1,i), len, MPI_REAL, nbr(i), tag,&

  comm, requests(i), ierr)

  Enddo

  Do i=1,n_neighbors

  Call MPI_Send(edge(1,i), len, MPI_REAL, nbr(i), tag,&

  comm, ierr)

  Enddo

  Call MPI_Waitall(n_neighbors, requests, statuses, ierr)

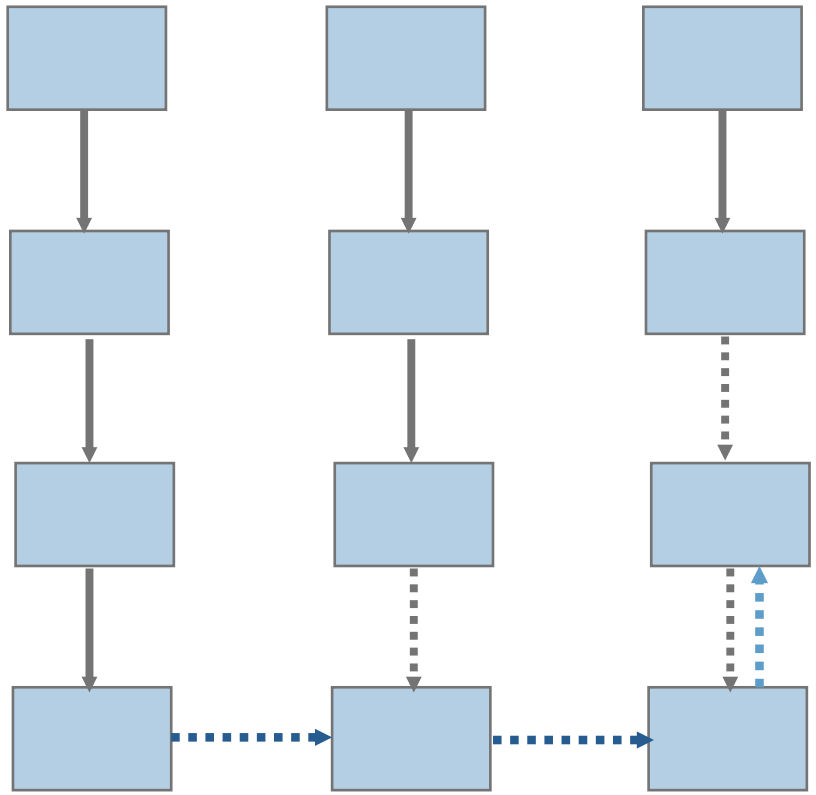
- Does not perform well in practice. Why?

Understanding the Behavior: Timing Model

- Sends interleave
- Sends block (data larger than buffering will allow)
- Sends control timing
- Receives do not interfere with Sends
- Exchange can be done in 4 steps (down, right, up, left)

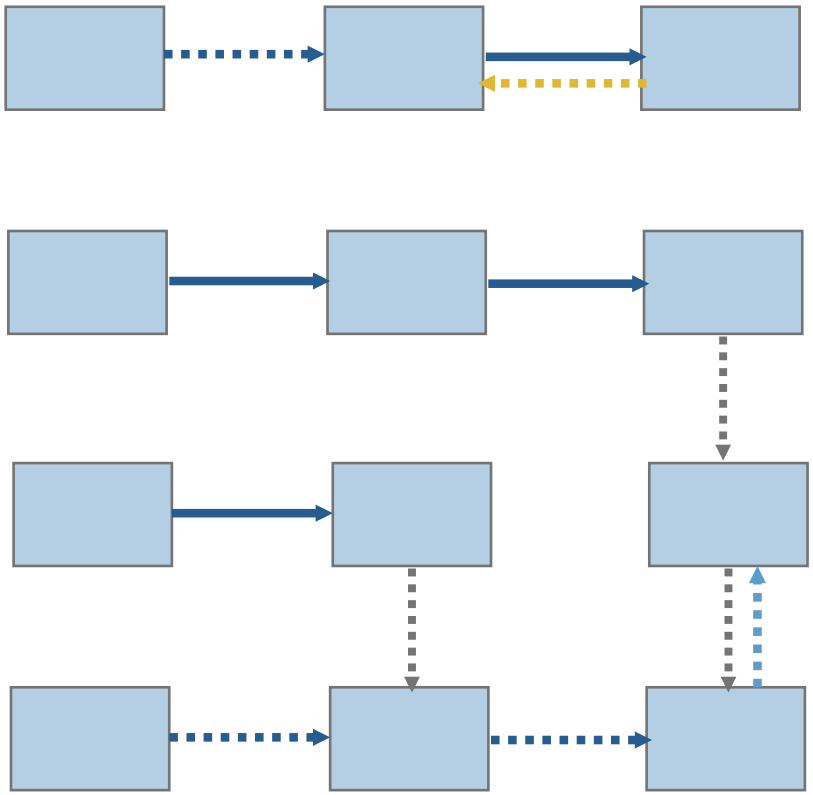
Mesh Exchange - Step 1

- Exchange data on a mesh



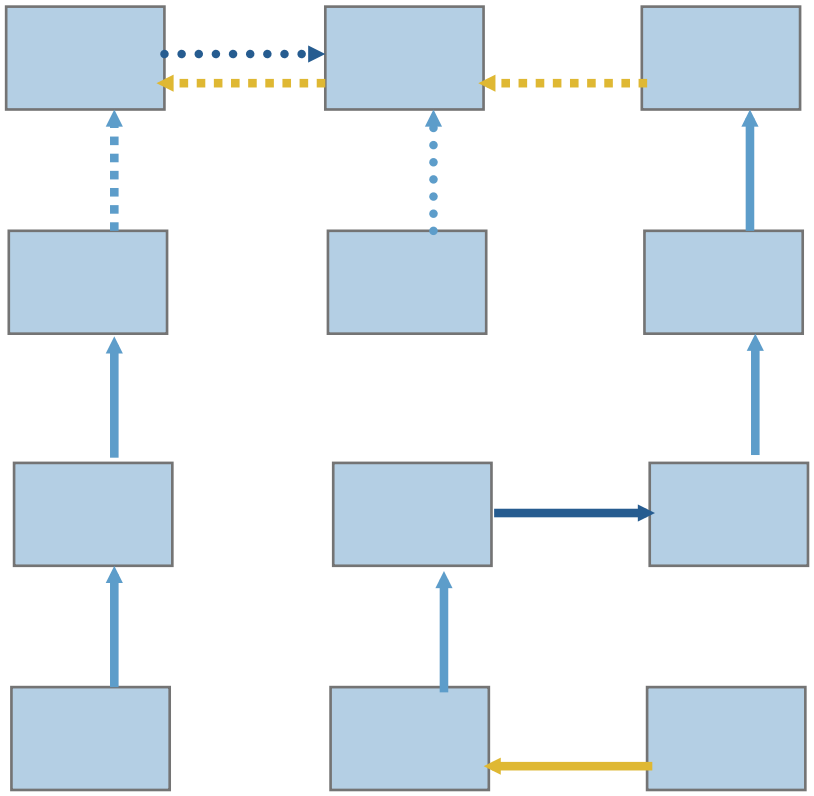
Mesh Exchange - Step 2

- Exchange data on a mesh



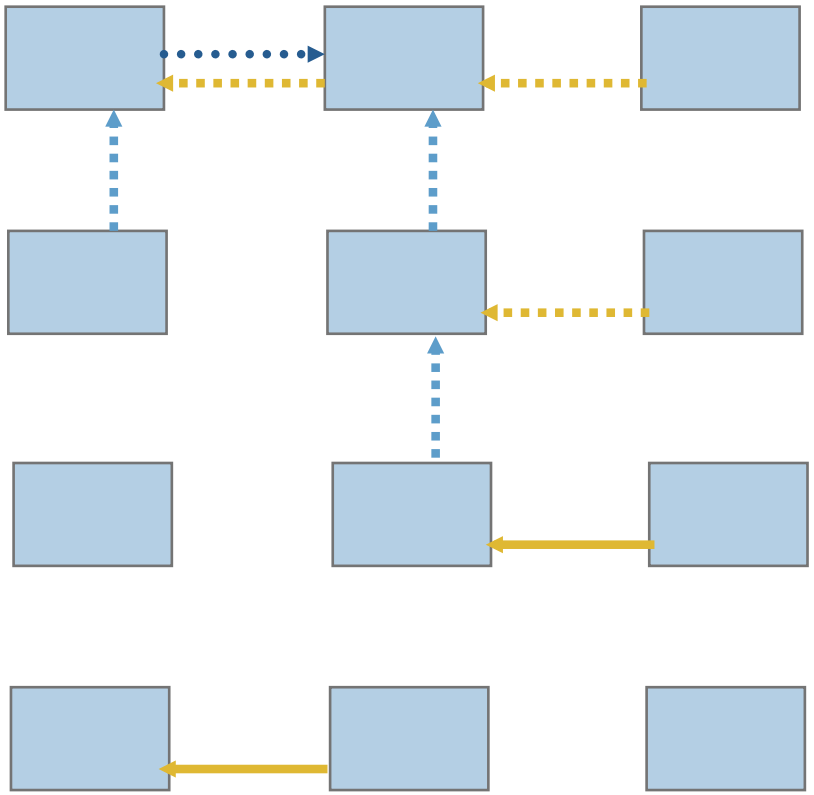
Mesh Exchange - Step 3

- Exchange data on a mesh



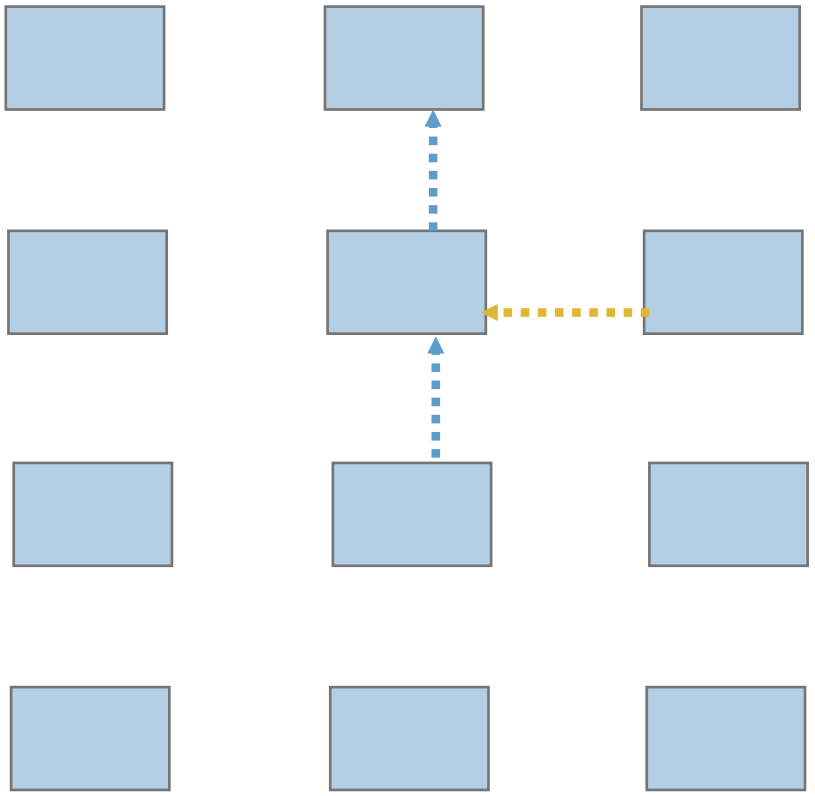
Mesh Exchange - Step 4

- Exchange data on a mesh



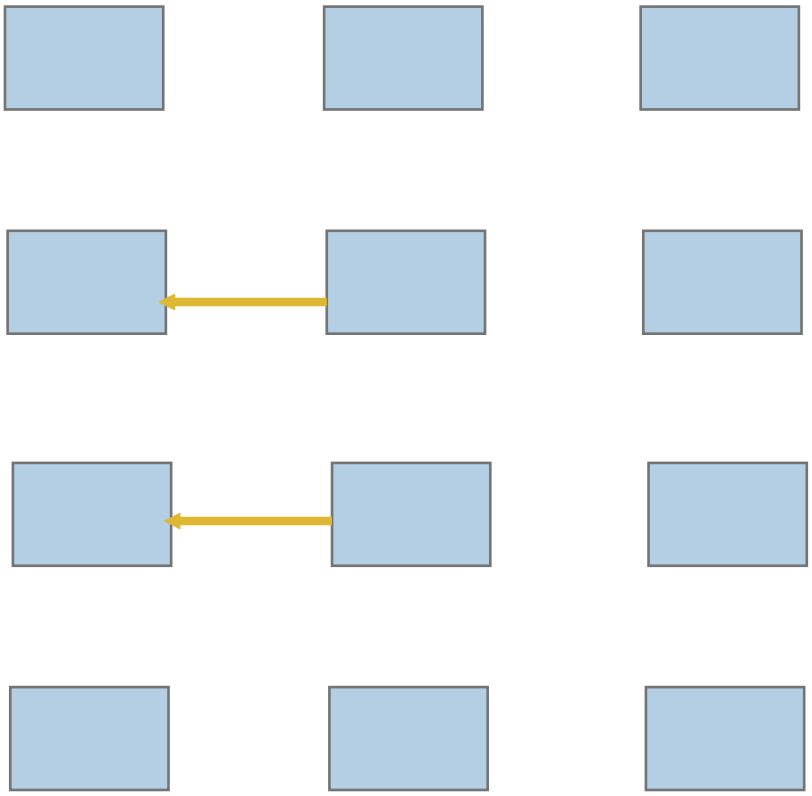
Mesh Exchange - Step 5

- Exchange data on a mesh

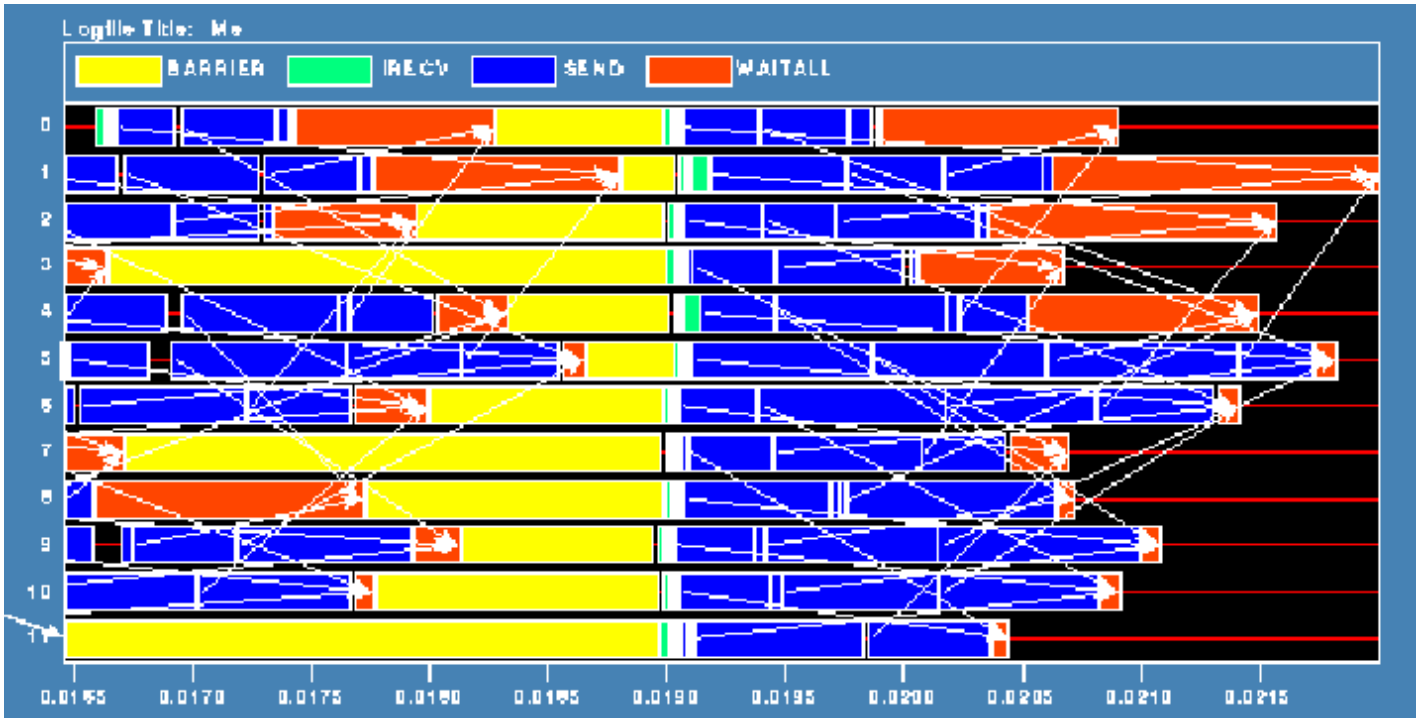


Mesh Exchange - Step 6

- Exchange data on a mesh

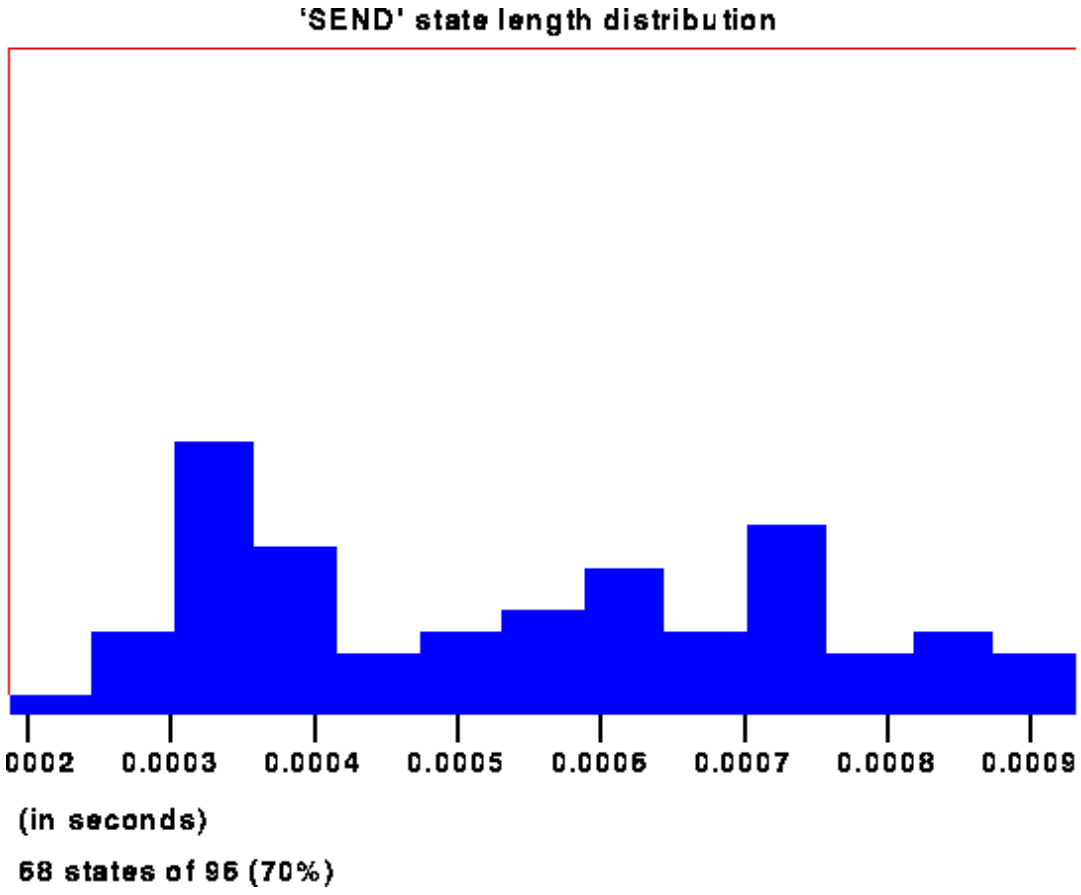


Timeline from IBM SP



- Note that process 1 finishes last, as predicted

Distribution of Sends



Why Six Steps?

- Ordering of Sends introduces delays when there is contention at the receiver
- Takes roughly twice as long as it should
- Bandwidth is being wasted
- Same thing would happen if using memcpy and shared memory

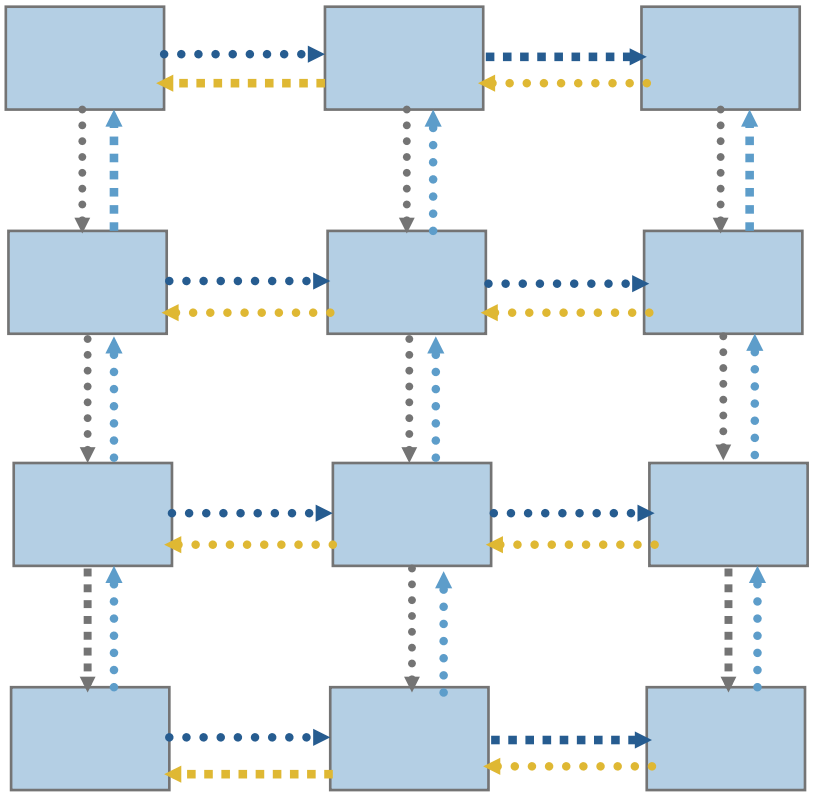
Fix 2: Use Isend and Irecv

- Do i=1,n_neighbors

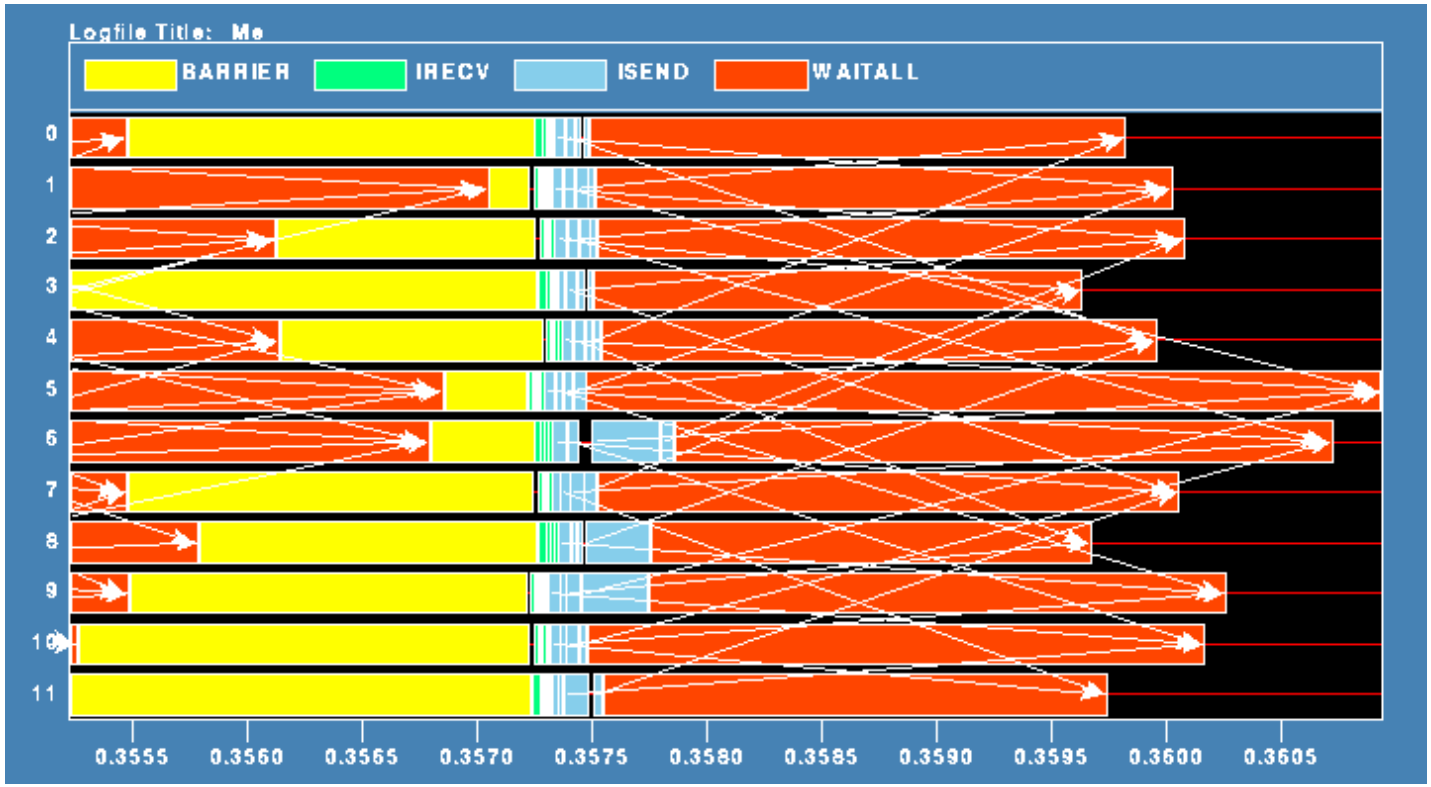
```
  Call MPI_Irecv(inedge(1,i),len,MPI_REAL,nbr(i),tag,&
                 comm, requests(i),ierr)
Enddo
Do i=1,n_neighbors
  Call MPI_Isend(edge(1,i), len, MPI_REAL, nbr(i), tag,&
                  comm, requests(n_neighbors+i), ierr)
Enddo
Call MPI_Waitall(2*n_neighbors, requests, statuses, ierr)
```

Mesh Exchange - Steps 1-4

- Four interleaved steps



Timeline from IBM SP



Note processes 5 and 6 are the only interior processors; these perform more communication than the other processors

Lesson: Defer Synchronization

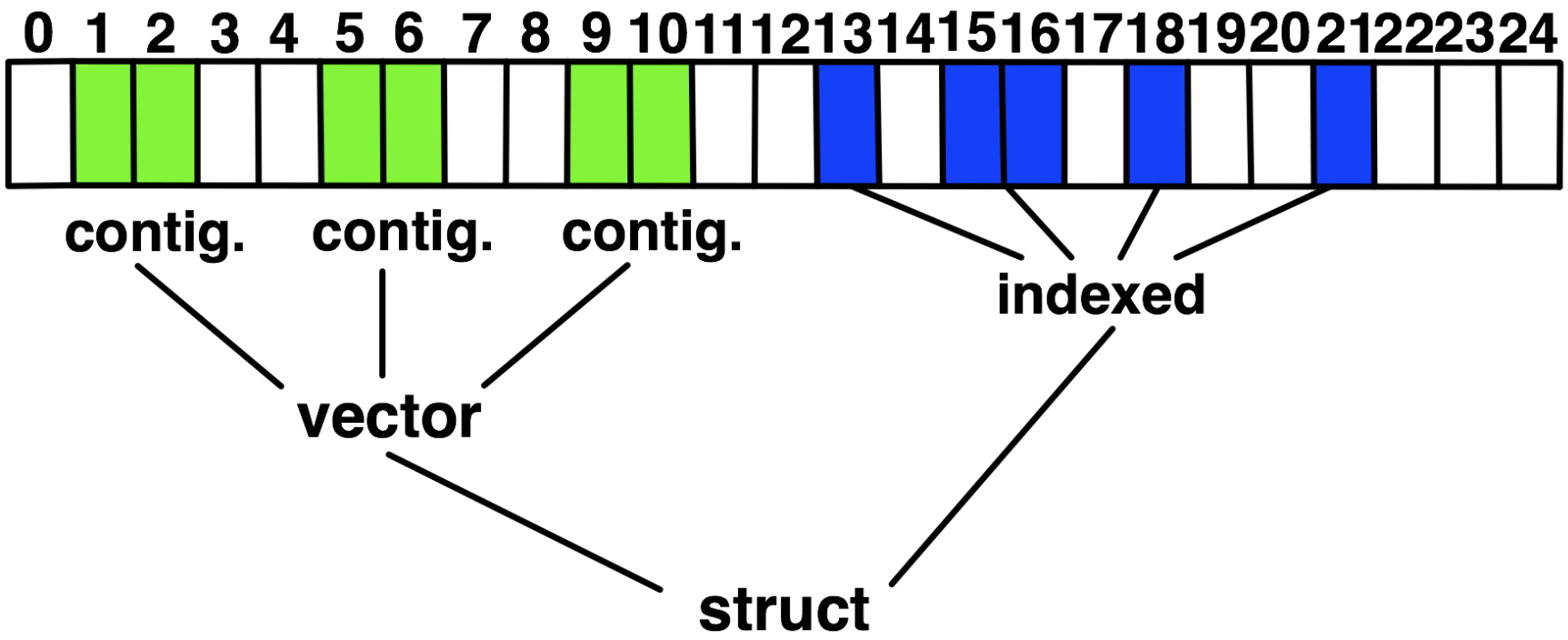
- Send-receive accomplishes two things:
  - Data transfer
  - Synchronization
- In many cases, there is more synchronization than required
- Use nonblocking operations and MPI_Waitall to defer synchronization

Datatypes

Introduction to Datatypes in MPI

- Datatypes allow users to serialize **arbitrary** data layouts into a message stream
  - Networks provide serial channels
  - Same for block devices and I/O
- Several constructors allow arbitrary layouts
  - Recursive specification possible
  - *Declarative* specification of data-layout
    - "what" and not "how", leaves optimization to implementation (*many unexplored* possibilities!)
  - Choosing the right constructors is not always simple

Derived Datatype Example



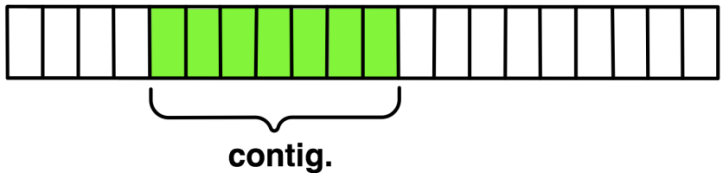
MPI's Intrinsic Datatypes

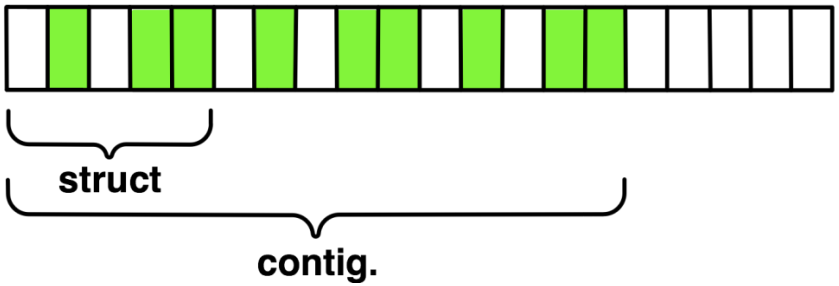
- Why intrinsic types?
  - Heterogeneity, nice to send a Boolean from C to Fortran
  - Conversion rules are complex, not discussed here
  - Length matches to language types
    - No sizeof(int) mess
- Users should generally use intrinsic types as basic types for communication and type construction!
  - MPI_BYTE should be avoided at all cost
- MPI-2.2 added some missing C types
  - E.g., unsigned long long

MPI_Type_contiguous

```
MPI_Type_contiguous(int count, MPI_Datatype
oldtype, MPI_Datatype *newtype)
```

- Contiguous array of oldtype
- Should not be used as last type (can be replaced by count)

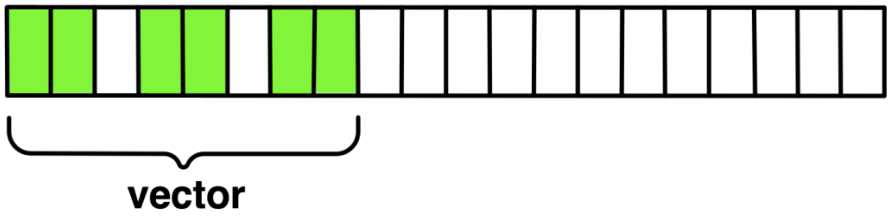


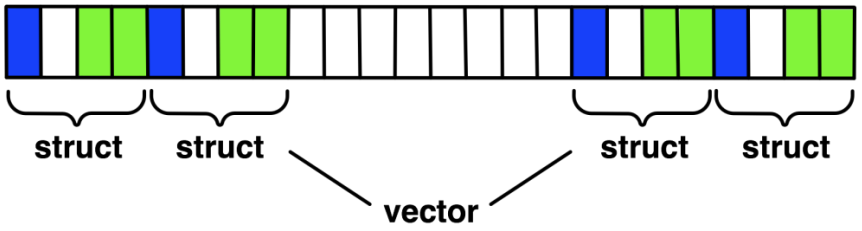


MPI_Type_vector

MPI_Type_vector(int count, int blocklength, int stride, MPI_Datatype oldtype, MPI_Datatype *newtype)

- Specify strided blocks of data of oldtype
- Very useful for Cartesian arrays

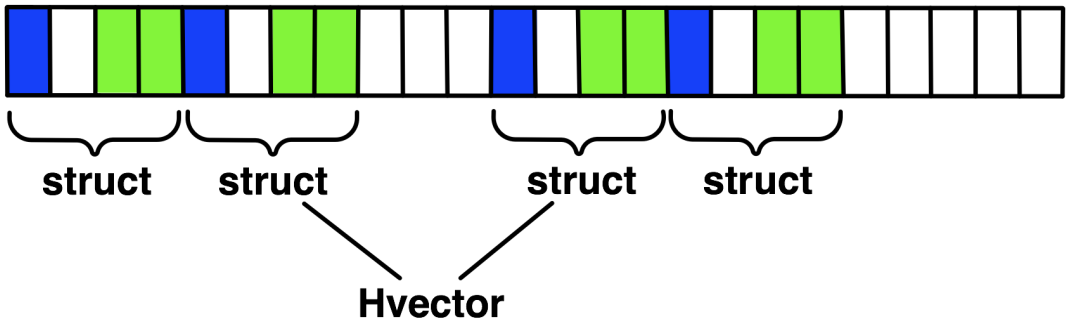




MPI_Type_create_hvector

MPI_Type_create_hvector(int count, int blocklength, MPI_Aint stride, MPI_Datatype oldtype, MPI_Datatype *newtype)

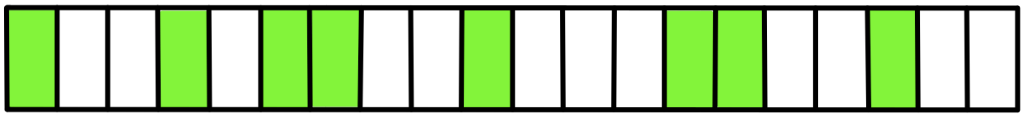
- Create non-unit strided vectors
- Useful for composition, e.g., vector of structs



MPI_Type_indexed

```
MPI_Type_indexed(int count, int *array_of_blocklengths,
int *array_of_displacements, MPI_Datatype oldtype,
MPI_Datatype *newtype)
```

- Pulling irregular subsets of data from a single array (cf. vector collectives)
  - dynamic codes with index lists, expensive though!

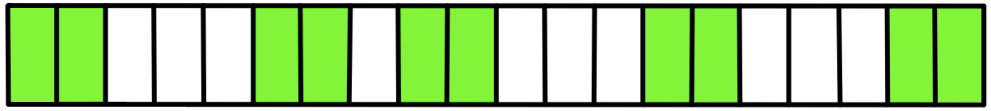


  - blen={1,1,2,1,2,1}
  - displs={0,3,5,9,13,17}

MPI_Type_create_indexed_block

```
MPI_Type_create_indexed_block(int count, int blocklength,
int *array_of_displacements, MPI_Datatype oldtype,
MPI_Datatype *newtype)
```

- Like Create_indexed but blocklength is the same

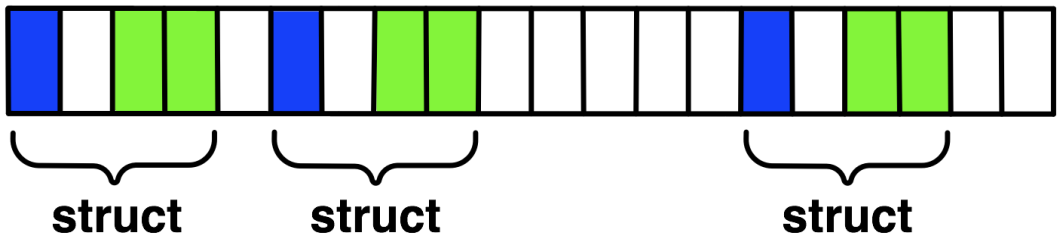


  - blen=2
  - displs={0,5,9,13,18}

MPI_Type_create_hindexed

```
MPI_Type_create_hindexed(int count, int *arr_of_blocklengths,
MPI_Aint *arr_of_displacements, MPI_Datatype oldtype,
MPI_Datatype *newtype)
```

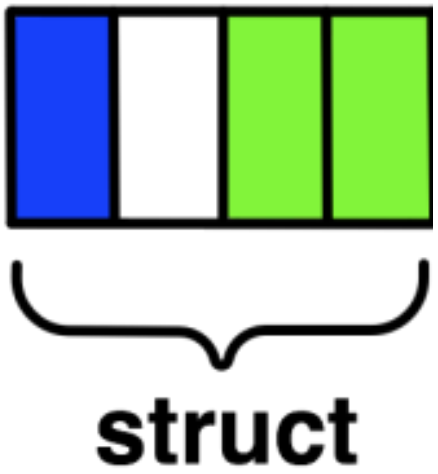
- Indexed with non-unit displacements, e.g., pulling types out of different arrays



MPI_Type_create_struct

```
MPI_Type_create_struct(int count, int array_of_blocklengths[],
MPI_Aint array_of_displacements[], MPI_Datatype
array_of_types[], MPI_Datatype *newtype)
```

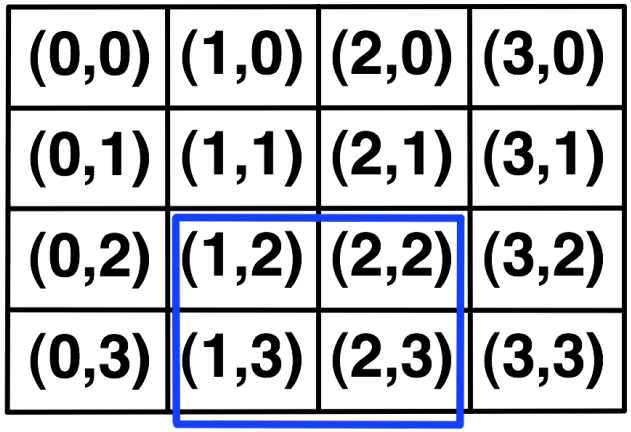
- Most general constructor, allows different types and arbitrary arrays (also most costly)



MPI_Type_create_subarray

```
MPI_Type_create_subarray(int ndims, int array_of_sizes[],
int array_of_subsizes[], int array_of_starts[], int order,
MPI_Datatype oldtype, MPI_Datatype *newtype)
```

- Specify subarray of n-dimensional array (sizes) by start (starts) and size (subsize)



MPI_Type_create_darray

```
MPI_Type_create_darray(int size, int rank, int ndims,
int array_of_gsizes[], int array_of_distribs[], int
array_of_dargs[], int array_of_psizes[], int order,
MPI_Datatype oldtype, MPI_Datatype *newtype)
```

- Create distributed array, supports block, cyclic and no distribution for each dimension
  - Very useful for I/O

(0,0)	(1,0)	(2,0)	(3,0)
(0,1)	(1,1)	(2,1)	(3,1)
(0,2)	(1,2)	(2,2)	(3,2)
(0,3)	(1,3)	(2,3)	(3,3)

MPI_BOTTOM and MPI_Get_address

- MPI_BOTTOM is the absolute zero address
  - Portability (e.g., may be non-zero in globally shared memory)
- MPI_Get_address
  - Returns address relative to MPI_BOTTOM
  - Portability (do not use “&” operator in C!)
- Very important to
  - build struct datatypes
  - If data spans multiple arrays

Commit, Free, and Dup

- Types must be committed before use
  - Only the ones that are used!
  - MPI_Type_commit may perform heavy optimizations (and will hopefully)
- MPI_Type_free
  - Free MPI resources of datatypes
  - Does not affect types built from it
- MPI_Type_dup
  - Duplicates a type
  - Library abstraction (composability)

Other Datatype Functions

- Pack/Unpack
  - Mainly for compatibility to legacy libraries
  - Avoid using it yourself
- Get_envelope/contents
  - Only for expert library developers
  - Libraries like MPITypes[1] make this easier
- MPI_Type_create_resized
  - Change extent and size (dangerous but useful)

http://www.mcs.anl.gov/mpitypes/

Datatype Selection Order

- Simple and effective performance model:
  - More parameters == slower
- **contig < vector < index_block < index < struct**
- Some (most) MPIs are inconsistent
  - But this rule is portable

W. Gropp et al.: Performance Expectations and Guidelines for MPI Derived Datatypes

Collectives and Nonblocking Collectives

Introduction to Collective Operations in MPI

- Collective operations are called by all processes in a communicator.
- **`MPI_BCAST`** distributes data from one process (the root) to all others in a communicator.
- **`MPI_REDUCE`** combines data from all processes in the communicator and returns it to one process.
- In many numerical algorithms, **`SEND/RECV`** can be replaced by **`BCAST/REDUCE`**, improving both simplicity and efficiency.

MPI Collective Communication

- Communication and computation is coordinated among a group of processes in a communicator
- Tags are not used; different communicators deliver similar functionality
- Non-blocking collective operations in MPI-3
- Three classes of operations: synchronization, data movement, collective computation

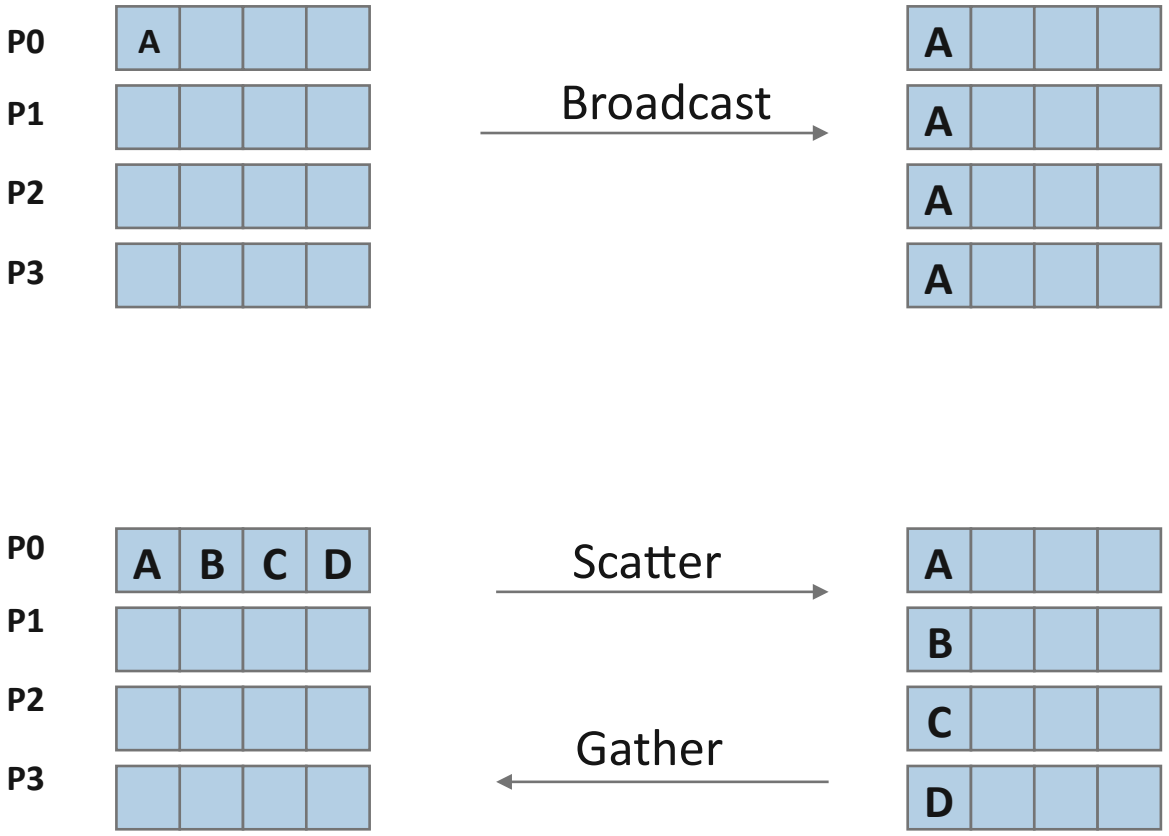
Synchronization

- **`MPI_BARRIER(comm)`**
  - Blocks until all processes in the group of communicator **`comm`** call it
  - A process cannot get out of the barrier until all other processes have reached barrier

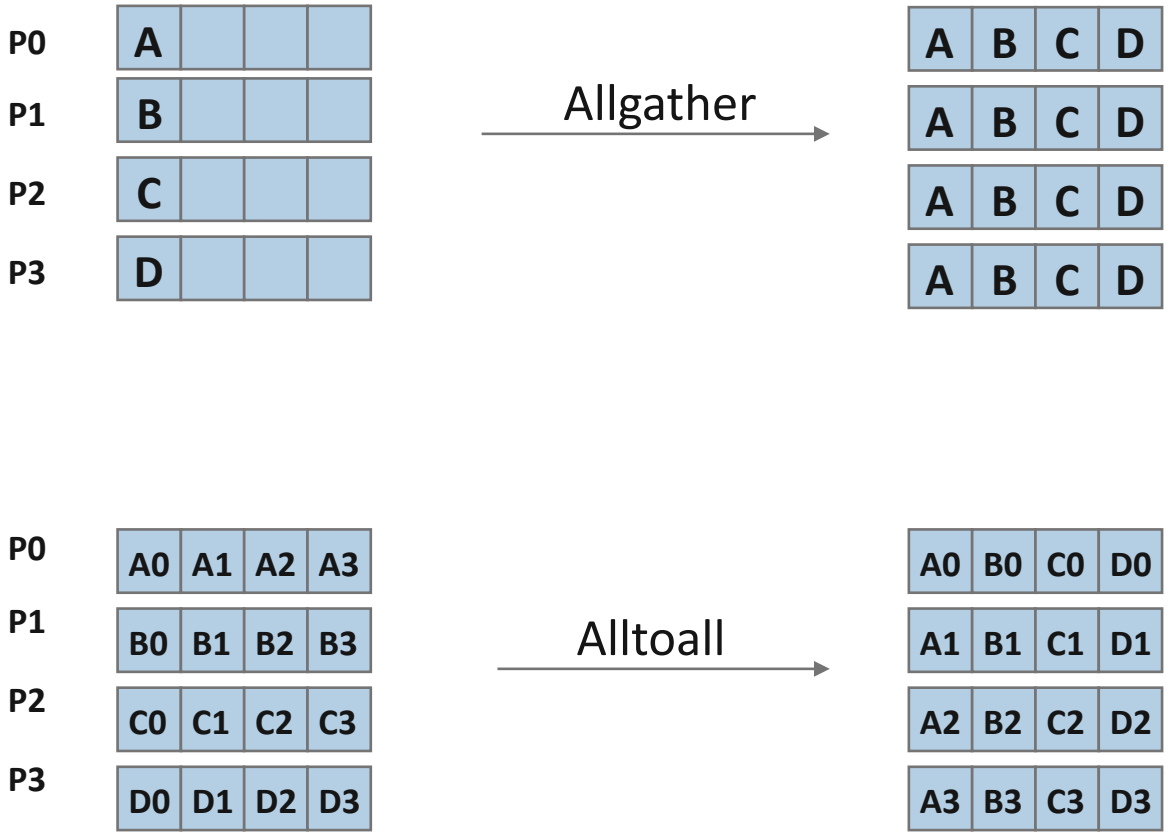
- Note that a barrier is rarely, if ever, necessary in an MPI program
- Adding barriers "just to be sure" is a bad practice and causes unnecessary synchronization. Remove unnecessary barriers from your code.

- One legitimate use of a barrier is before the first call to MPI_Wtime to start a timing measurement. This is to ensure that all processes start that portion of the code at the same time.
- Avoid using barriers other than for this.

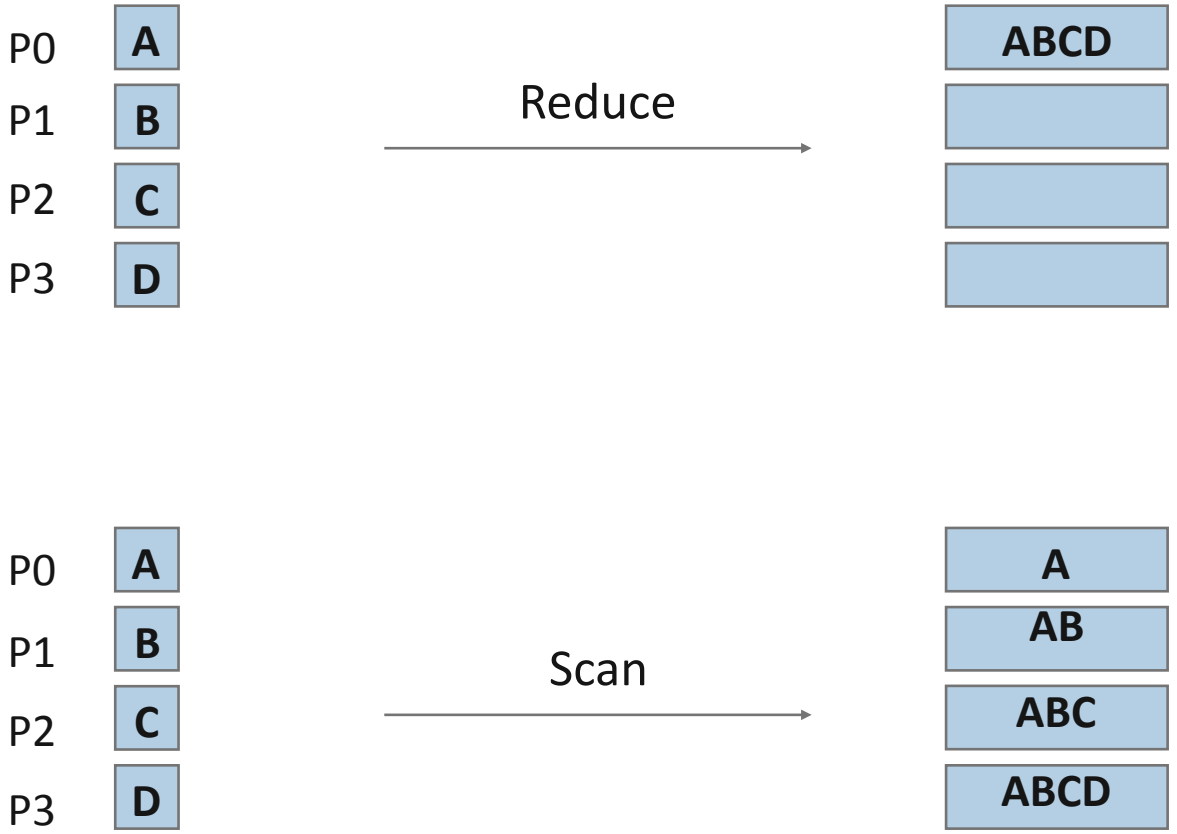
Collective Data Movement



More Collective Data Movement



Collective Computation



MPI Collective Routines

- Many Routines: **`MPI_ALLGATHER`**, **`MPI_ALLGATHERV`**, **`MPI_ALLREDUCE`**, **`MPI_ALLTOALL`**, **`MPI_ALLTOALLV`**, **`MPI_BCAST`**, **`MPI_GATHER`**, **`MPI_GATHERV`**, **`MPI_REDUCE`**, **`MPI_REDUCESCATTER`**, **`MPI_SCAN`**, **`MPI_SCATTER`**, **`MPI_SCATTERV`**
- "**`All`**" versions deliver results to all participating processes
- "**`V`**" versions (stands for vector) allow the chunks to have different sizes
- **`MPI_ALLREDUCE`**, **`MPI_REDUCE`**, **`MPI_REDUCESCATTER`**, and **`MPI_SCAN`** take both built-in and user-defined combiner functions

MPI Built-in Collective Computation Operations

MPI_MAX	Maximum
MPI_MIN	Minimum
MPI_PROD	Product
MPI_SUM	Sum
MPI_LAND	Logical and
MPI_LOR	Logical or
MPI_LXOR	Logical exclusive or
MPI_BAND	Bitwise and
MPI_BOR	Bitwise or
MPI_BXOR	Bitwise exclusive or
MPI_MAXLOC	Maximum and location
MPI_MINLOC	Minimum and location

Defining your own Collective Operations

- Create your own collective computations with:

```
MPI_OP_CREATE(user_fn, commutes, &op);
MPI_OP_FREE(&op);

user_fn(invec, inoutvec, len, datatype);
```

- The user function should perform:

```
inoutvec[i] = invec[i] op inoutvec[i];
```

for i from 0 to len-1

- The user function can be non-commutative, but must be associative

Nonblocking Collectives

Nonblocking Collective Communication

- Nonblocking communication
  - Deadlock avoidance
  - Overlapping communication/computation
- Collective communication
  - Collection of pre-defined optimized routines
- Nonblocking collective communication
  - Combines both advantages
  - System noise/imbalance resiliency
  - Semantic advantages

Nonblocking Communication

- Semantics are simple:
  - Function returns no matter what
  - No progress guarantee!
- E.g., MPI_Isend(<send-args>, MPI_Request *req);
- Nonblocking tests:
  - Test, Testany, Testall, Testsome
- Blocking wait:
  - Wait, Waitany, Waitall, Waitsome

Nonblocking Collective Communication

- Nonblocking variants of all collectives
  - MPI_Ibcast(<bcast args>, MPI_Request *req);
- Semantics:
  - Function returns no matter what
  - No guaranteed progress (quality of implementation)
  - Usual completion calls (wait, test) + mixing
  - Out-of order completion
- Restrictions:
  - No tags, in-order matching
  - Send and vector buffers may not be touched during operation
  - MPI_Cancel not supported
  - No matching with blocking collectives

Hoefler et al.: Implementation and Performance Analysis of Non-Blocking Collective Operations for MPI

Nonblocking Collective Communication

- Semantic advantages:
  - Enable asynchronous progression (and manual)
    - Software pipelinling
  - Decouple data transfer and synchronization
    - Noise resiliency!
  - Allow overlapping communicators
    - See also neighborhood collectives
  - Multiple outstanding operations at any time
    - Enables pipelining window

Hoefler et al.: Implementation and Performance Analysis of Non-Blocking Collective Operations for MPI

A Non-Blocking Barrier?

- What can that be good for? Well, quite a bit!
- Semantics:
  - MPI_Ibarrier() – calling process entered the barrier, **no** synchronization happens
  - Synchronization **may** happen asynchronously
  - MPI_Test/Wait() – synchronization happens **if** necessary
- Uses:
  - Overlap barrier latency (small benefit)
  - Use the split semantics! Processes **notify** non-collectively but **synchronize** collectively!

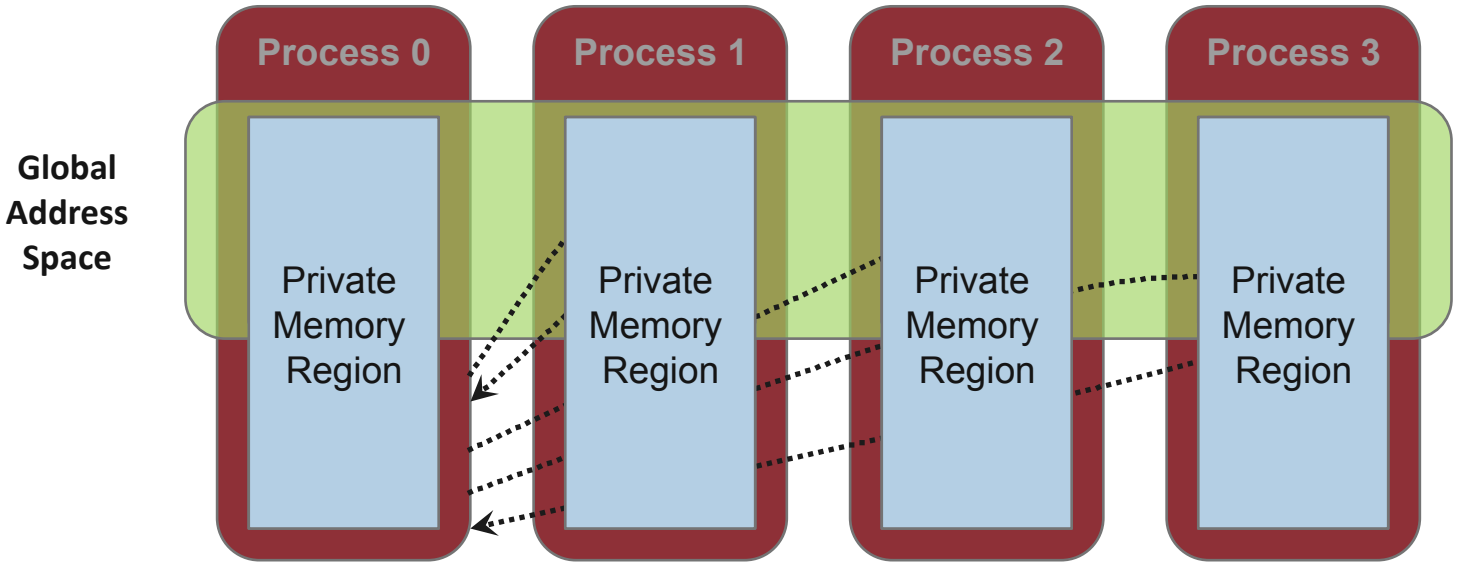
Nonblocking And Collective Summary

- Nonblocking comm does two things:
  - Overlap and relax synchronization
- Collective comm does one thing
  - Specialized pre-optimized routines
  - Performance portability
  - Hopefully transparent performance
- They can be composed
  - E.g., software pipelining

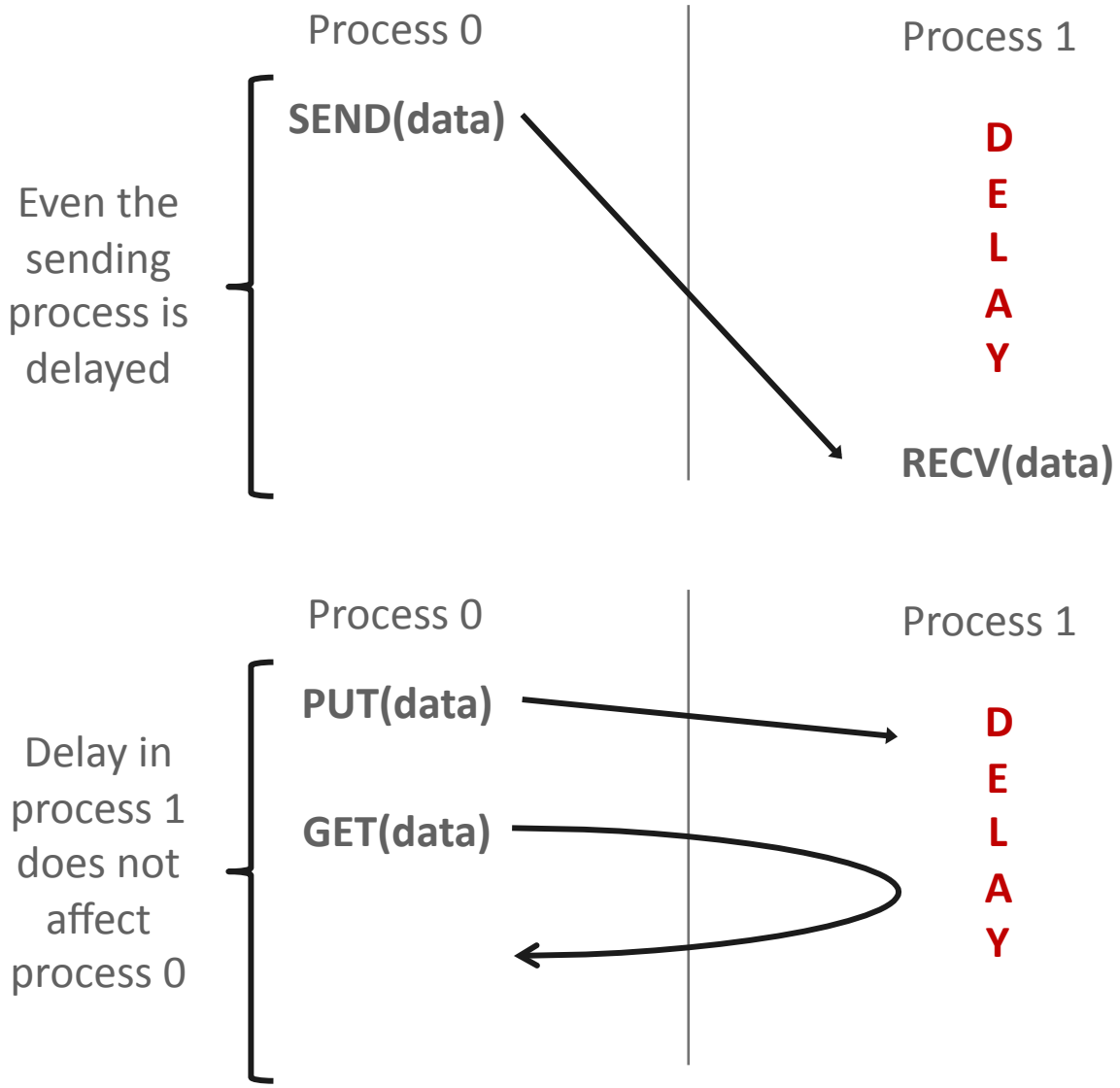
One-Sided Communication

One-Sided Communication

- The basic idea of one-sided communication models is to decouple data movement with process synchronization
  - Should be able to move data without requiring that the remote process synchronize
  - Each process exposes a part of its memory to other processes
  - Other processes can directly read from or write to this memory



Comparing One-sided and Two-sided Programming



Advantages of RMA Operations

- Can do multiple data transfers with a single synchronization operation
  - like BSP model
- Bypass tag matching
  - effectively precomputed as part of remote offset
- Some irregular communication patterns can be more economically expressed
- Can be significantly faster than send/receive on systems with hardware support for remote memory access, such as shared memory systems

Irregular Communication Patterns with RMA

- If communication pattern is not known *a priori*, the send-recv model requires an extra step to determine how many sends-recvs to issue
- RMA, however, can handle it easily because only the origin or target process needs to issue the put or get call
- This makes dynamic communication easier to code in RMA

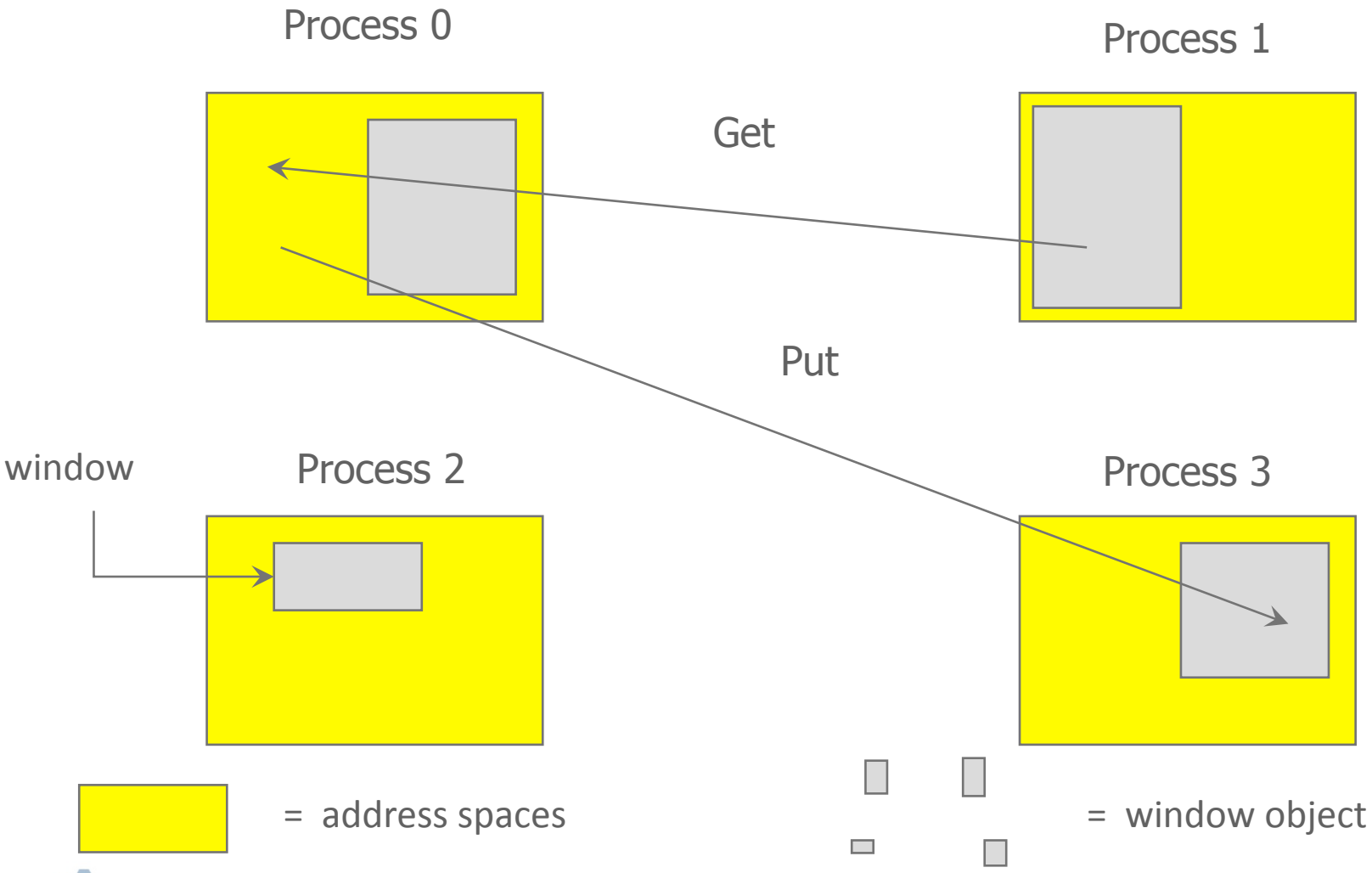
What we need to know in MPI RMA

- How to create remote accessible memory?
- Reading, Writing and Updating remote memory
- Data Synchronization
- Memory Model

Creating Public Memory

- Any memory created by a process is, by default, only locally accessible
  - X = malloc(100);
- Once the memory is created, the user has to make an explicit MPI call to declare a memory region as remotely accessible
  - MPI terminology for remotely accessible memory is a "window"
  - A group of processes collectively create a "window"
- Once a memory region is declared as remotely accessible, all processes in the window can read/write data to this memory without explicitly synchronizing with the target process

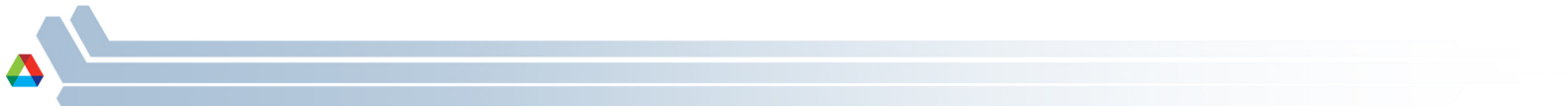
Remote Memory Access Windows and Window Objects



Basic RMA Functions for Communication

- **`MPI_Win_create`** exposes local memory to RMA operation by other processes in a communicator
  - Collective operation
  - Creates window object
- **`MPI_Win_free`** deallocates window object

- **`MPI_Put`** moves data from local memory to remote memory
- **`MPI_Ge`**t retrieves data from remote memory into local memory
- **`MPI_Accumulate`** updates remote memory using local values
- Data movement operations are non-blocking
- **Subsequent synchronization on window object needed to ensure operation is complete**



Window creation models

- Four models exist
  - MPI_WIN_CREATE
    - You already have an allocated buffer that you would like to make remotely accessible
  - MPI_WIN_ALLOCATE
    - You want to create a buffer and directly make it remotely accessible
  - MPI_WIN_CREATE_DYNAMIC
    - You don't have a buffer yet, but will have one in the future
  - MPI_WIN_ALLOCATE_SHARED
    - You want multiple processes on the same node share a buffer
    - We will not cover this model today

MPI_WIN_CREATE

```
int MPI_Win_create(void *base, MPI_Aint size,
                   int disp_unit, MPI_Info info,
                   MPI_Comm comm, MPI_Win *win)
```

- Expose a region of memory in an RMA window
  - Only data exposed in a window can be accessed with RMA ops.
- Arguments:
  - base - pointer to local data to expose
  - size - size of local data in bytes (nonnegative integer)
  - disp_unit - local unit size for displacements, in bytes (positive integer)
  - info - info argument (handle)
  - comm - communicator (handle)

Example with MPI_WIN_CREATE

```
int main(int argc, char ** argv)
{
    int *a;    MPI_Win win;

    MPI_Init(&argc, &argv);

    /* create private memory */
    a = (void *) malloc(1000 * sizeof(int));
    /* use private memory like you normally would */
    a[0] = 1;  a[1] = 2;

    /* collectively declare memory as remotely accessible */
    MPI_Win_create(a, 1000*sizeof(int), sizeof(int), MPI_INFO_NULL,
                   MPI_COMM_WORLD, &win);

    /* Array 'a' is now accessibly by all processes in
     * MPI_COMM_WORLD */

    MPI_Win_free(&win);

    MPI_Finalize(); return 0;
}
```

MPI_WIN_ALLOCATE

```
int MPI_Win_allocate(MPI_Aint size, int disp_unit,
MPI_Info info,
             MPI_Comm comm, void *baseptr, MPI_Win *win)
```

- Create a remotely accessible memory region in an RMA window
  - Only data exposed in a window can be accessed with RMA ops.
- Arguments:
  - size - size of local data in bytes (nonnegative integer)
  - disp_unit - local unit size for displacements, in bytes (positive integer)
  - info - info argument (handle)
  - comm - communicator (handle)
  - baseptr - pointer to exposed local data

Example with MPI_WIN_ALLOCATE

```
int main(int argc, char ** argv)
{
    int *a;    MPI_Win win;

    MPI_Init(&argc, &argv);

    /* collectively create remotely accessible memory in the
   window */
    MPI_Win_allocate(1000*sizeof(int), sizeof(int), MPI_INFO_NULL,
                     MPI_COMM_WORLD, &a, &win);

    /* Array 'a' is now accessibly by all processes in
     * MPI_COMM_WORLD */

    MPI_Win_free(&win);

    MPI_Finalize(); return 0;
}
```

MPI_WIN_CREATE_DYNAMIC

```
int MPI_Win_create_dynamic(…, MPI_Comm comm, MPI_Win *win)
```

- Create an RMA window, to which data can later be attached
  - Only data exposed in a window can be accessed with RMA ops
- Application can dynamically attach memory to this window
- Application can access data on this window only after a memory region has been attached

Example with MPI_WIN_CREATE_DYNAMIC

```
int main(int argc, char ** argv)
{
    int *a;    MPI_Win win;

    MPI_Init(&argc, &argv);
    MPI_Win_create_dynamic(MPI_INFO_NULL, MPI_COMM_WORLD, &win);

    /* create private memory */
    a = (void *) malloc(1000 * sizeof(int));
    /* use private memory like you normally would */
    a[0] = 1;  a[1] = 2;

    /* locally declare memory as remotely accessible */
    MPI_Win_attach(win, a, 1000*sizeof(int));

    /*Array 'a' is now accessibly by all processes in MPI_COMM_WORLD*/

    /* undeclare public memory */
    MPI_Win_detach(win, a);
    MPI_Win_free(&win);

   MPI_Finalize(); return 0;
}
```

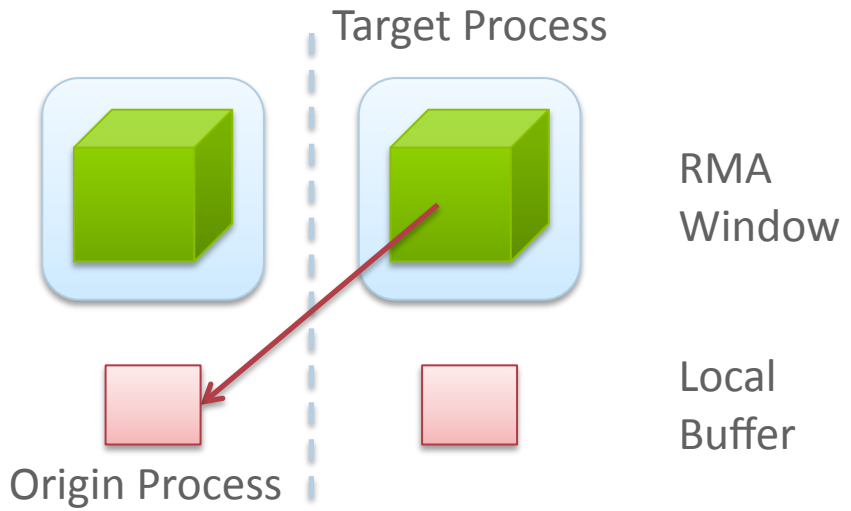
Data movement

- MPI provides ability to read, write and atomically modify data in remotely accessible memory regions
  - MPI_GET
  - MPI_PUT
  - MPI_ACCUMULATE
  - MPI_GET_ACCUMULATE
  - MPI_COMPARE_AND_SWAP
  - MPI_FETCH_AND_OP

Data movement: *Get*

```
MPI_Get(
    origin_addr, origin_count, origin_datatype,
    target_rank,
    target_disp, target_count, target_datatype,
    win)
```

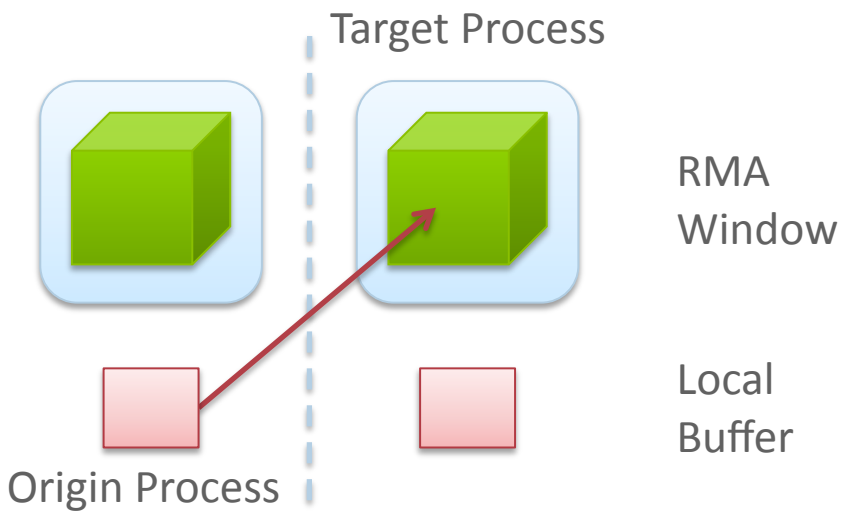
- Move data to origin, from target
- Separate data description triples for origin and target



Data movement: *Put*

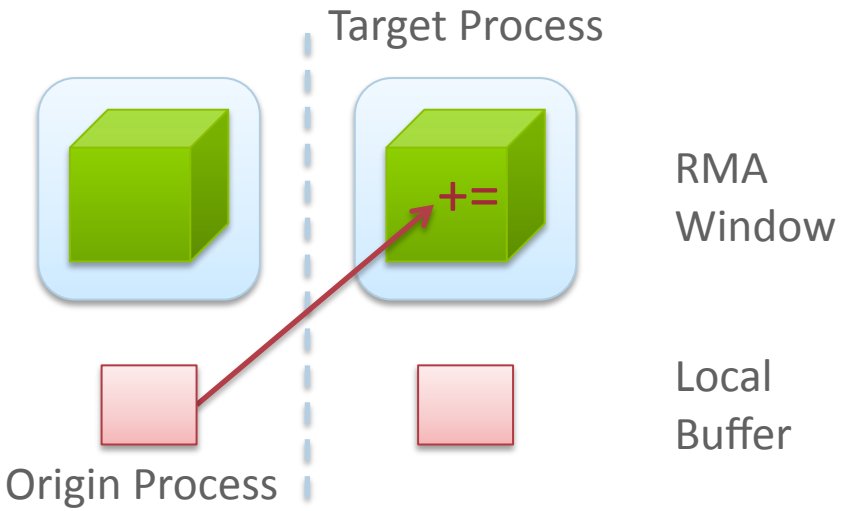
```
MPI_Put(
    origin_addr, origin_count, origin_datatype,
    target_rank,
    target_disp, target_count, target_datatype,
    win)
```

- Move data from origin, to target
- Same arguments as MPI_Get



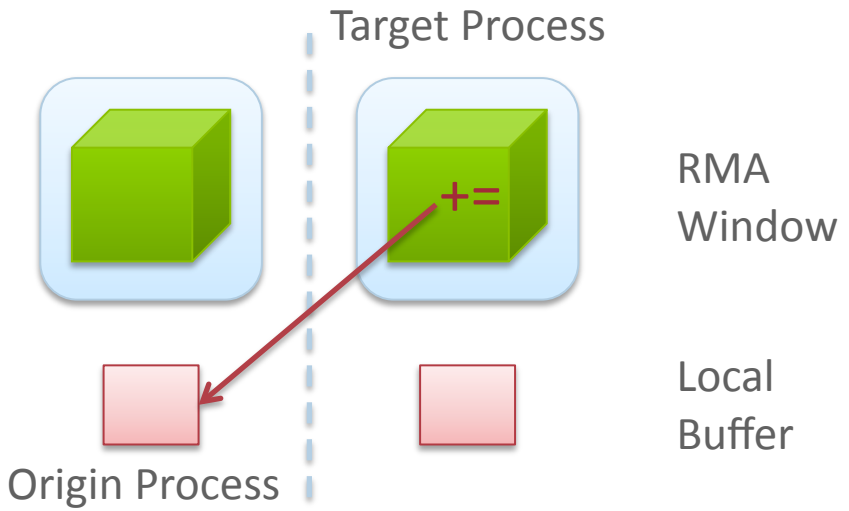
Data aggregation: *Accumulate*

- Like MPI_Put, but applies an MPI_Op instead
  - Predefined ops only, no user-defined!
- Result ends up at target buffer
- Different data layouts between target/origin OK, basic type elements must match
- Put-like behavior with MPI_REPLACE (implements *f(a,b)=b*)
  - Atomic PUT



Data aggregation: *Get Accumulate*

- Like MPI_Get, but applies an MPI_Op instead
  - Predefined ops only, no user-defined!
- Result at target buffer; original data comes to the source
- Different data layouts between target/origin OK, basic type elements must match
- Get-like behavior with MPI_NO_OP
  - Atomic GET



Ordering of Operations in MPI RMA

- For Put/Get operations, ordering does not matter
  - If you do two concurrent PUTs to the same location, the result can be garbage
- Two accumulate operations to the same location are valid
  - If you want "atomic PUTs", you can do accumulates with MPI_REPLACE
- All accumulate operations are ordered by default
  - User can tell the MPI implementation that (s)he does not require ordering as optimization hints
  - You can ask for "read-after-write" ordering, "write-after-write" ordering, or "read-after-read" ordering

Additional Atomic Operations

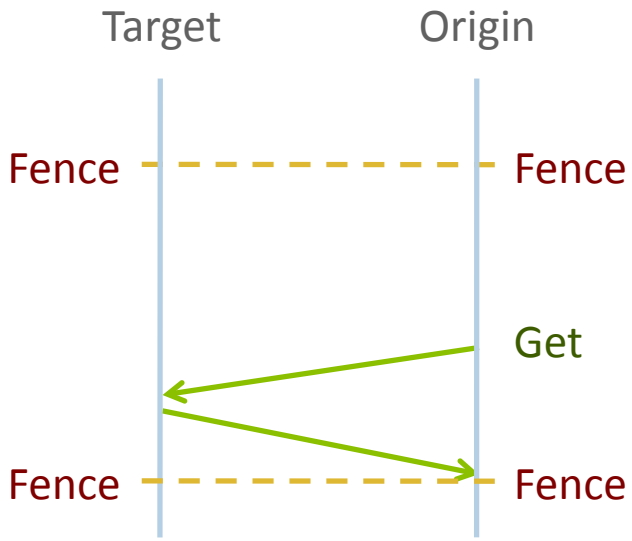
- Compare-and-swap
  - Compare the target value with an input value; if they are the same, replace the target with some other value
  - Useful for linked list creations – if next pointer is NULL, do something
- Fetch-and-Op
  - Special case of Get accumulate for predefined datatypes – faster for the hardware to implement

RMA Synchronization Models

- RMA data visibility
  - When is a process allowed to read/write from remotely accessible memory?
  - How do I know when data written by process X is available for process Y to read?
  - RMA synchronization models provide these capabilities
- MPI RMA model allows data to be accessed only within an "epoch"
  - Three types of epochs possible:
    - Fence (active target)
    - Post-start-complete-wait (active target)
    - Lock/Unlock (passive target)
- Data visibility is managed using RMA synchronization primitives
  - MPI_WIN_FLUSH, MPI_WIN_FLUSH_ALL
  - Epochs also perform synchronization

Fence Synchronization

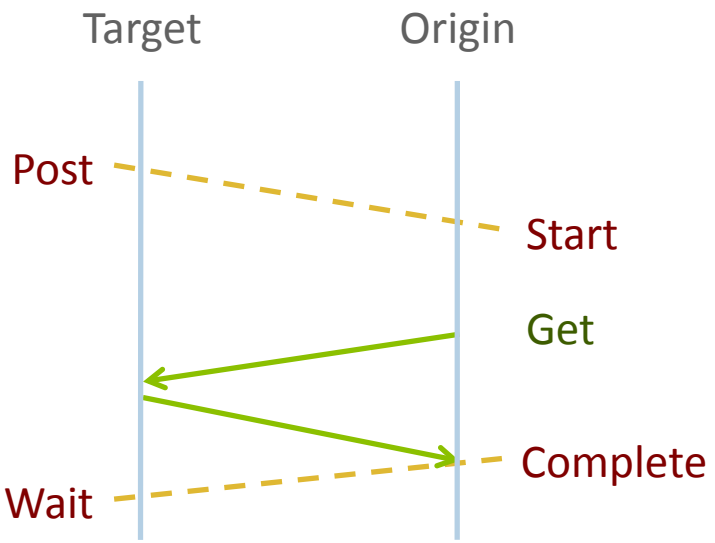
- `MPI_Win_fence(assert, win)`
- Collective synchronization model -- assume it synchronizes like a barrier
- Starts *and* ends access & exposure epochs (usually)



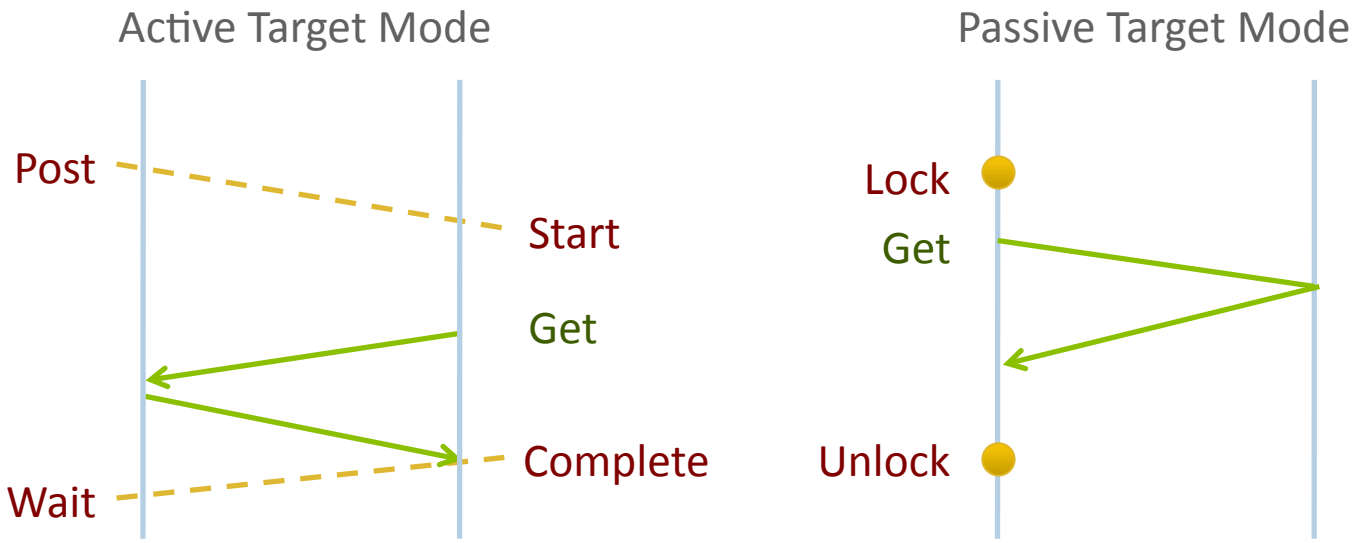
- Everyone does an MPI_WIN_FENCE to open an epoch
- Everyone issues PUT/GET operations to read/ write data
- Everyone does an MPI_WIN_FENCE to close the epoch

PSCW Synchronization

- Target: Exposure epoch
  - Opened with MPI_Win_post
  - Closed by MPI_Win_wait
- Origin: Access epoch
  - Opened by MPI_Win_start
  - Closed by MPI_Win_compete
- All may block, to enforce P-S/C-W ordering
  - Processes can be both origins and targets
- Like FENCE, but the target may allow a smaller group of processes to access its data



Lock/Unlock Synchronization



- Passive mode: One-sided, *asynchronous* communication
  - Target does **not** participate in communication operation
- Shared memory like model

Passive Target Synchronization

```
int MPI_Win_lock(int lock_type, int rank, int assert,
      MPI_Win win)

int MPI_Win_unlock(int rank, MPI_Win win)
```

- Begin/end passive mode epoch
  - Doesn't function like a mutex, name can be confusing
  - Communication operations within epoch are all nonblocking
- Lock type
  - SHARED: Other processes using shared can access concurrently
  - EXCLUSIVE: No other processes can access concurrently

When should I use passive mode?

- RMA performance advantages from low protocol overheads
  - Two-sided: Matching, queueing, buffering, unexpected receives, etc…
  - Direct support from high-speed interconnects (e.g. InfiniBand)
- Passive mode: *asynchronous* one-sided communication
  - Data characteristics:
    - Big data analysis requiring memory aggregation
    - Asynchronous data exchange
    - Data-dependent access pattern
  - Computation characteristics:
    - Adaptive methods (e.g. AMR, MADNESS)
    - Asynchronous dynamic load balancing
- Common structure: shared arrays

Topology Mapping and Neighborhood Collectives

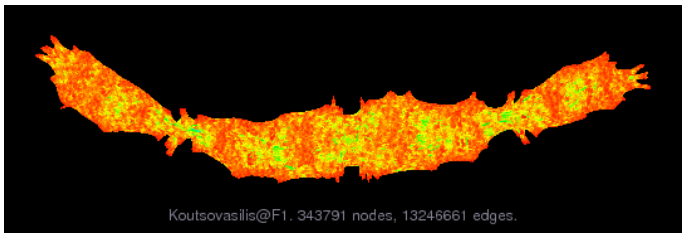
Topology Mapping Basics

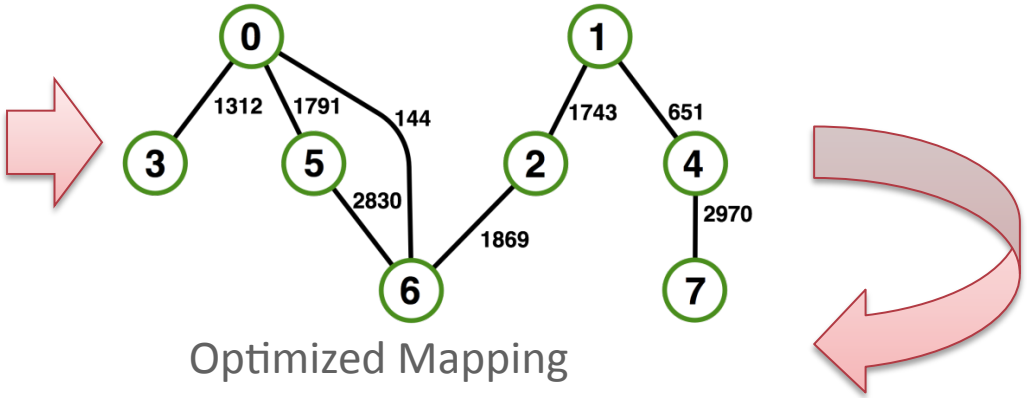
- First type: Allocation mapping
  - Up-front specification of communication pattern
  - Batch system picks good set of nodes for given topology
- Properties:
  - Not widely supported by current batch systems
  - Either predefined allocation (BG/P), random allocation, or “global bandwidth maximation”
  - Also problematic to specify communication pattern upfront, not always possible (or static)

Topology Mapping Basics

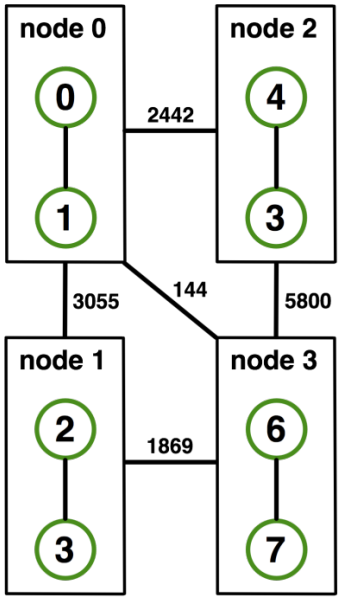
- Rank reordering
  - Change numbering in a given allocation to reduce congestion or dilation
  - Sometimes automatic (early IBM SP machines)
- Properties
  - Always possible, but effect may be limited (e.g., in a bad allocation)
  - Portable way: MPI process topologies
    - Network topology is not exposed
  - Manual data shuffling after remapping step

On-Node Reordering



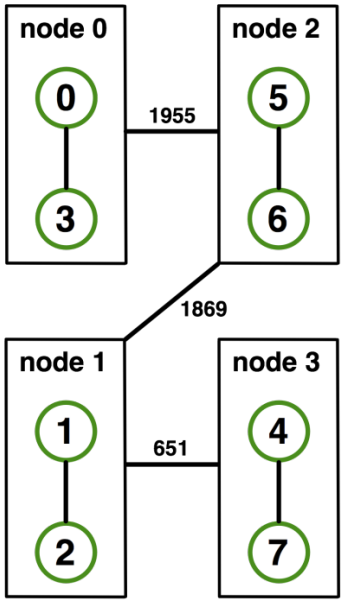


Naïve Mapping

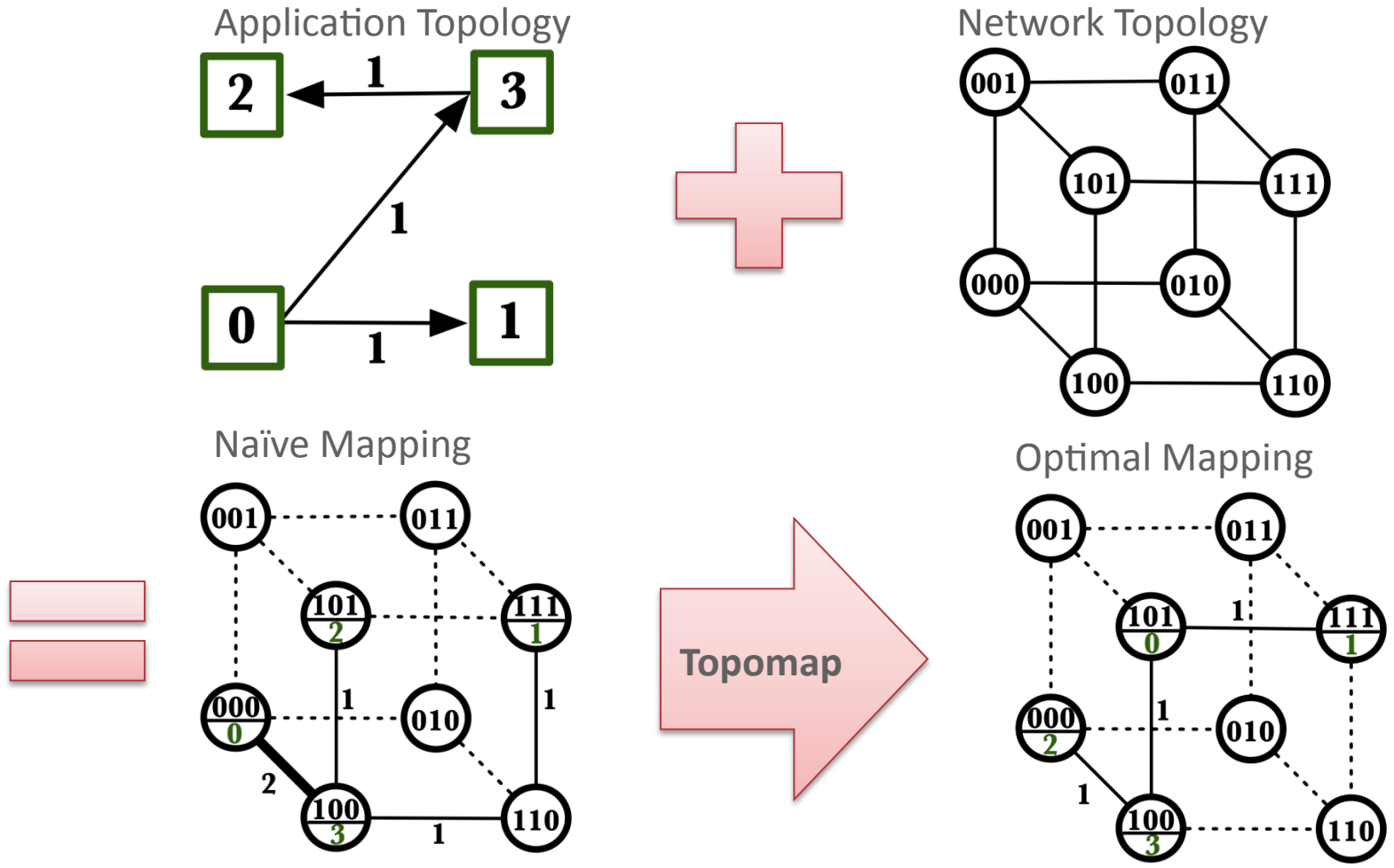


Topomap

Optimized Mapping



Off-Node (Network) Reordering



MPI Topology Intro

- Convenience functions (in MPI-1)
  - Create a graph and query it, nothing else
  - Useful especially for Cartesian topologies
    - Query neighbors in n-dimensional space
  - Graph topology: each rank specifies full graph ☹
- Scalable Graph topology (MPI-2.2)
  - Graph topology: each rank specifies its neighbors **or** an arbitrary subset of the graph
- Neighborhood collectives (MPI-3.0)
  - Adding communication functions defined on graph topologies (neighborhood of distance one)

MPI_Cart_create

```
MPI_Cart_create(MPI_Comm comm_old, int ndims, const int
*dims, const int *periods, int reorder, MPI_Comm *comm_cart)
```

- Specify ndims-dimensional topology
  - Optionally periodic in each dimension (Torus)
- Some processes may return MPI_COMM_NULL
  - Product of dims must be <= P
- Reorder argument allows for topology mapping
  - Each calling process may have a new rank in the created communicator
  - Data has to be remapped manually

MPI_Cart_create Example

```
int dims[3] = {5,5,5};
int periods[3] = {1,1,1};
MPI_Comm topocomm;
MPI_Cart_create(comm, 3, dims, periods, 0, &topocomm);
```

- But we're starting MPI processes with a one-dimensional argument (-p X)
  - User has to determine size of each dimension
  - Often as "square" as possible, MPI can help!

MPI_Dims_create

```
MPI_Dims_create(int nnodes, int ndims, int *dims)
```

- Create dims array for Cart_create with nnodes and ndims
  - Dimensions are as close as possible (well, in theory)
- Non-zero entries in dims will not be changed
  - nnodes must be multiple of all non-zeroes

MPI_Dims_create Example

```
int p;
MPI_Comm_size(MPI_COMM_WORLD, &p);
MPI_Dims_create(p, 3, dims);

int periods[3] = {1,1,1};
MPI_Comm topocomm;
MPI_Cart_create(comm, 3, dims, periods, 0, &topocomm);
```

- Makes life a little bit easier
  - Some problems may be better with a non-square layout though

Cartesian Query Functions

- Library support and convenience!
- MPI_Cartdim_get()
  - Gets dimensions of a Cartesian communicator
- MPI_Cart_get()
  - Gets size of dimensions
- MPI_Cart_rank()
  - Translate coordinates to rank
- MPI_Cart_coords()
  - Translate rank to coordinates

Cartesian Communication Helpers

```
MPI_Cart_shift(MPI_Comm comm, int direction, int disp,
int *rank_source, int *rank_dest)
```

- Shift in one dimension
  - Dimensions are numbered from 0 to ndims-1
  - Displacement indicates neighbor distance (-1, 1, …)
  - May return MPI_PROC_NULL
- Very convenient, all you need for nearest neighbor communication

MPI_Graph_create

- Don't use! Use one of the Dist_graph functions instead

```
MPI_Graph_create(MPI_Comm comm_old, int nnodes, const int *index, const int *edges, int reorder, MPI_Comm *comm_graph)
```

- nnodes is the total number of nodes
- index i stores the total number of neighbors for the first i nodes (sum)
  - Acts as offset into edges array
- edges stores the edge list for all processes
  - Edge list for process j starts at index[j] in edges
  - Process j has index[j+1]-index[j] edges

Distributed graph constructor

- MPI_Graph_create is discouraged
  - Not scalable
  - Not deprecated yet but hopefully soon
- New distributed interface:
  - Scalable, allows distributed graph specification
    - Either local neighbors **or** any edge in the graph
  - Specify edge weights
    - Meaning undefined but optimization opportunity for vendors!
  - Info arguments
    - Communicate assertions of semantics to the MPI library
    - E.g., semantics of edge weights

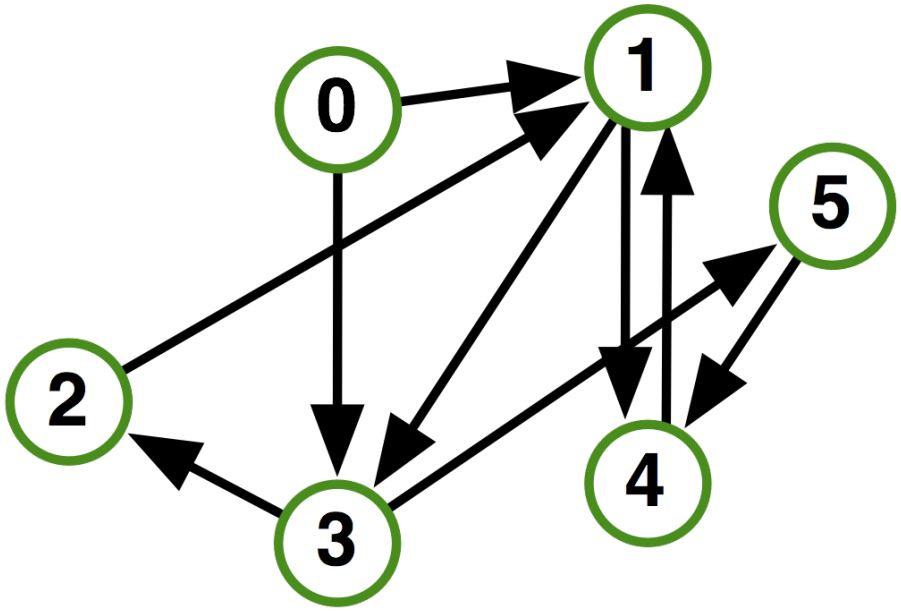
MPI_Dist_graph_create_adjacent

```
MPI_Dist_graph_create_adjacent(MPI_Comm comm_old, int
indegree, const int sources[], const int sourceweights[], int
outdegree, const int destinations[], const int destweights[],
MPI_Info info,int reorder, MPI_Comm *comm_dist_graph)
```

- indegree, sources, ~weights – source proc. Spec.
- outdegree, destinations, ~weights – dest. proc. spec.
- info, reorder, comm_dist_graph – as usual
- directed graph
- Each edge is specified twice, once as out-edge (at the source) and once as in-edge (at the dest)

MPI_Dist_graph_create_adjacent

- Process 0:
  - Indegree: 0
  - Outdegree: 2
  - Dests: {3,1}
- Process 1:
  - Indegree: 3
  - Outdegree: 2
  - Sources: {4,0,2}
  - Dests: {3,4}
- …



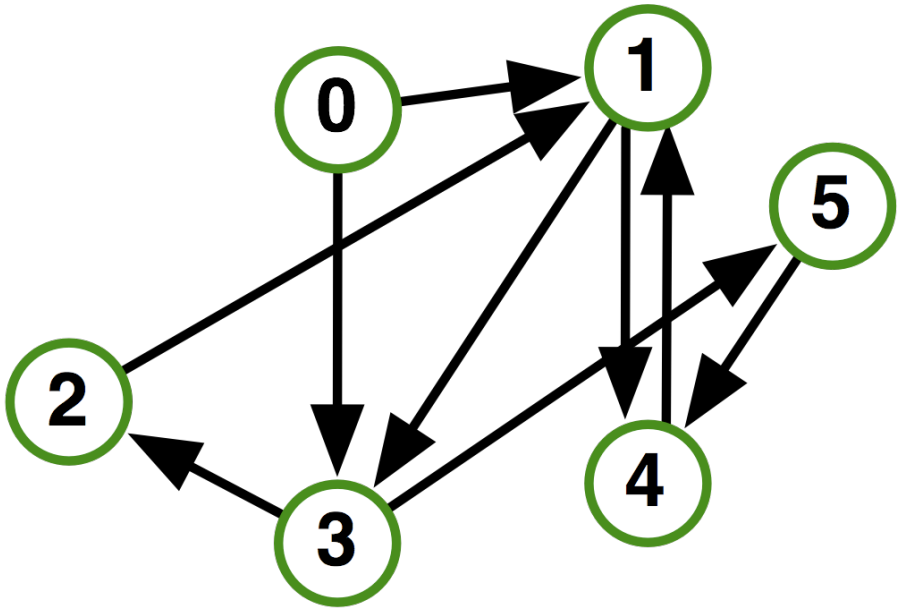
MPI_Dist_graph_create

```
MPI_Dist_graph_create(MPI_Comm comm_old, int n, const int
sources[], const int degrees[], const int destinations[], const
int weights[], MPI_Info info, int reorder, MPI_Comm
*comm_dist_graph)
```

- n – number of source nodes
- sources – n source nodes
- degrees – number of edges for each source
- destinations, weights – dest. processor specification
- info, reorder – as usual
- More flexible and convenient
  - Requires global communication
  - Slightly more expensive than adjacent specification

MPI_Dist_graph_create

- Process 0:
  - N: 2
  - Sources: {0,1}
  - Degrees: {2,2}
  - Dests: {3,1,4,3}
- Process 1:
  - N: 2
  - Sources: {2,3}
  - Degrees: {1,1}
  - Dests: {1,2}
- …



Distributed Graph Neighbor Queries

- MPI_Dist_graph_neighbors_count()

```
MPI_Dist_graph_neighbors_count(MPI_Comm comm, int
*indegree,int *outdegree, int *weighted)
```

  - Query the number of neighbors of **calling process**
  - Returns indegree and outdegree!
  - Also info if weighted

- MPI_Dist_graph_neighbors()
  - Query the neighbor list of **calling process**
  - Optionally return weights

```
MPI_Dist_graph_neighbors(MPI_Comm comm, int
maxindegree, int sources[], int sourceweights[], int
maxoutdegree, int destinations[],int destweights[])
```

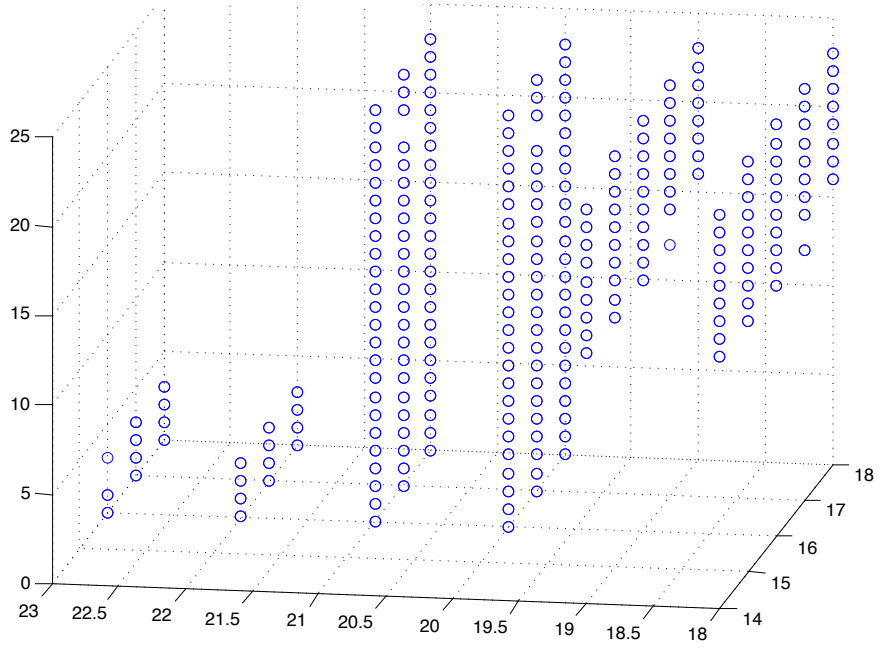
Further Graph Queries

```
MPI_Topo_test(MPI_Comm comm, int *status)
```

- Status is either:
  - MPI_GRAPH (ugs)
  - MPI_CART
  - MPI_DIST_GRAPH
  - MPI_UNDEFINED (no topology)
- Enables to write libraries on top of MPI topologies!

Algorithms and Topology

- Complex hierarchy:
  - Multiple chips per node; different access to local memory and to interconnect; multiple cores per chip
  - Mesh has different bandwidths in different directions
  - Allocation of nodes may not be regular (you are unlikely to get a compact brick of nodes)
  - Some nodes have GPUs
- Most algorithms designed for simple hierarchies and ignore network issues



Recent work on general topology mapping e.g.,

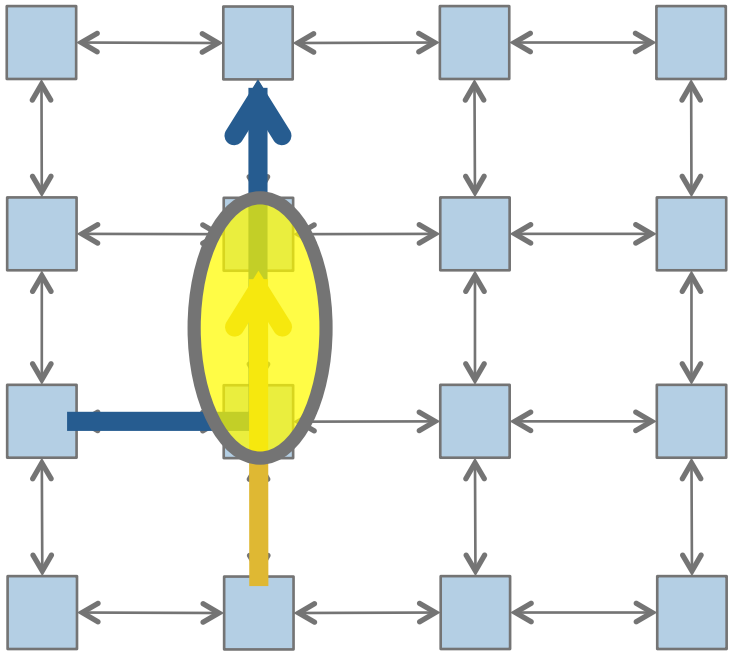
Generic Topology Mapping Strategies for Large-scale Parallel Architectures, Hoefler and Snir

Dynamic Workloads Require New, More Integrated Approaches

- Performance irregularities mean that classic approaches to decomposition are increasingly ineffective
  - Irregularities come from OS, runtime, process/thread placement, memory, heterogeneous nodes, power/clock frequency management
- Static partitioning tools can lead to persistent load imbalances
  - Mesh partitioners have incorrect cost models, no feedback mechanism
  - "Regrid when things get bad" won't work if the cost model is incorrect; also costly
- Basic building blocks must be more dynamic without introducing too much overhead

Communication Cost Includes More than Latency and Bandwidth

- Communication does not happen in isolation
- Effective bandwidth on shared link is ½ point-to-point bandwidth
- Real patterns can involve many more (integer factors)
- Loosely synchronous algorithms ensure communication cost is worst case



Halo Exchange on BG/Q and Cray XE6

- 2048 doubles to each neighbor
- Rate is MB/sec (for all tables)

BG/Q	**8 Neighbors**	
	Irecv/Send	Irecv/Isend
World	662	1167
Even/Odd	711	1452
1 sender		2873

Cray XE6	**8 Neighbors**	
	Irecv/Send	Irecv/Isend
World	352	348
Even/Odd	338	324
1 sender		5507

Discovering Performance Opportunities

- Lets look at a single process sending to its neighbors.
- Based on our performance model, we *expect* the rate to be roughly twice that for the halo (since this test is only sending, not sending and receiving)

System	4 neighbors		8 Neighbors	
		Periodic		Periodic
BG/L	488	490	389	389
BG/P	1139	1136	892	892
BG/Q			2873	
XT3	1005	1007	1053	1045
XT4	1634	1620	1773	1770
XE6			5507	

Discovering Performance Opportunities

- Ratios of a single sender to all processes sending (in rate)
- *Expect* a factor of roughly 2 (since processes must also receive)

System	4 neighbors		8 Neighbors	
		Periodic		Periodic
BG/L	2.24		2.01	
BG/P	3.8		2.2	
BG/Q			1.98	
XT3	7.5	8.1	9.08	9.41
XT4	10.7	10.7	13.0	13.7
XE6			15.6	15.9

- BG gives roughly double the halo rate. XTn and XE6 are much higher.
  - It should be possible to improve the halo exchange on the XT by scheduling the communication
  - Or improving the MPI implementation

Neighborhood Collectives

Neighborhood Collectives

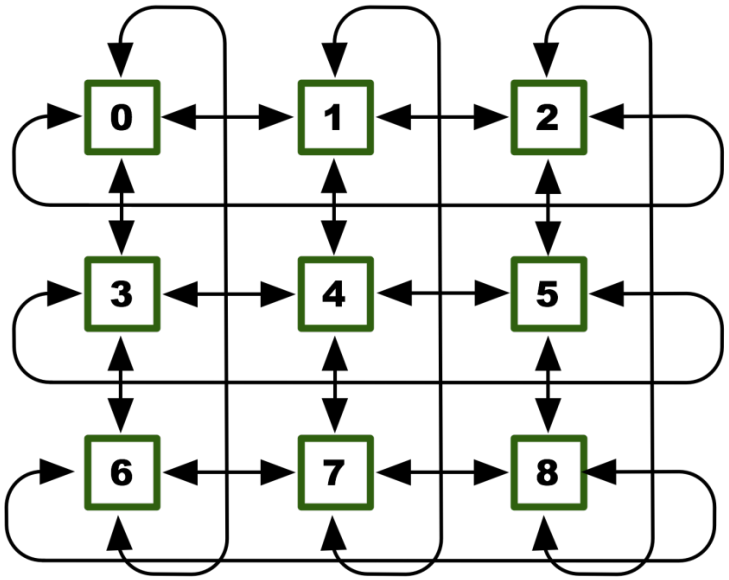
- Topologies implement no communication!
  - Just helper functions
- Collective communications only cover some patterns
  - E.g., no stencil pattern
- Several requests for “build your own collective” functionality in MPI
  - Neighborhood collectives are a simplified version
  - Cf. Datatypes for communication patterns!

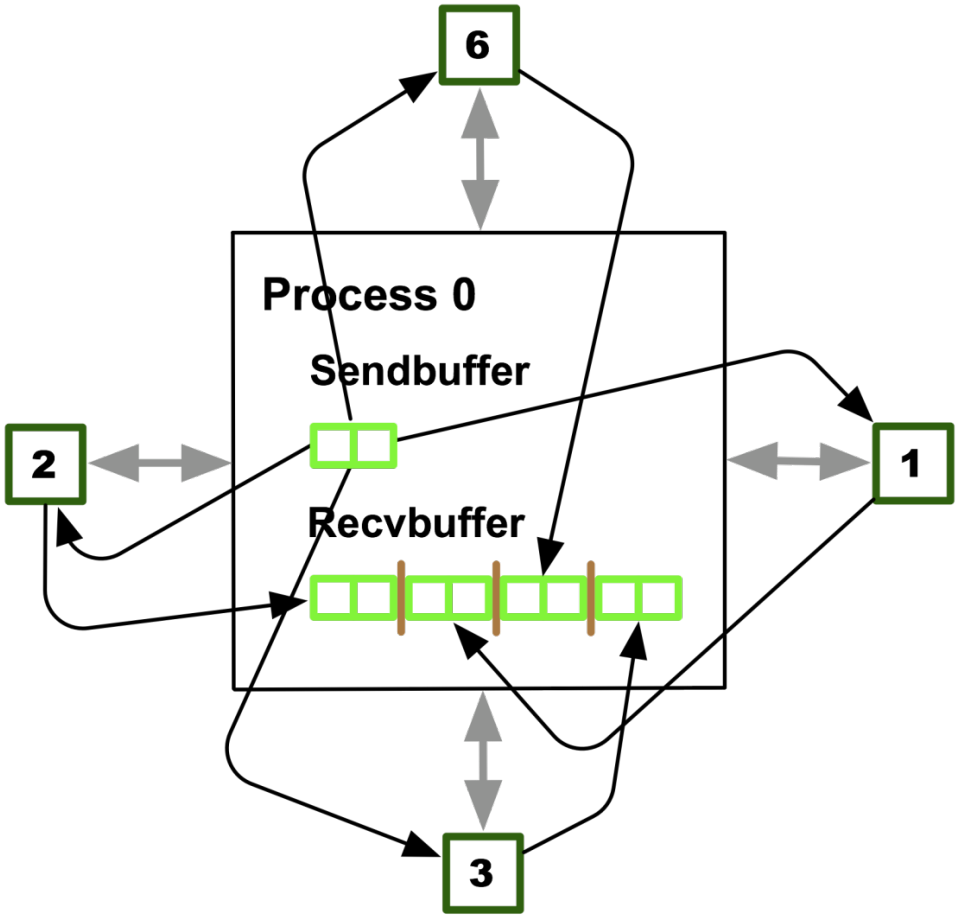
Cartesian Neighborhood Collectives

- Communicate with direct neighbors in Cartesian topology
  - Corresponds to cart_shift with disp=1
  - Collective (all processes in comm must call it, including processes without neighbors)
  - Buffers are laid out as neighbor sequence:
    - Defined by order of dimensions, first negative, then positive
    - 2*ndims sources and destinations
    - Processes at borders (MPI_PROC_NULL) leave holes in buffers (will not be updated or communicated)!

Cartesian Neighborhood Collectives

- Allgather
- Buffer ordering example:





Graph Neighborhood Collectives

- Collective Communication along arbitrary neighborhoods
  - Order is determined by order of neighbors as returned by (dist_) graph_neighbors.
  - Distributed graph is directed, may have different numbers of send/ recv neighbors
  - Can express dense collective operations ☺
  - Any persistent communication pattern!

MPI_Neighbor_allgather

```
MPI_Neighbor_allgather(const void* sendbuf, int sendcount,
MPI_Datatype sendtype, void* recvbuf, int recvcount,
MPI_Datatype recvtype, MPI_Comm comm)
```

- Sends the same message to all neighbors
- Receives indegree distinct messages
- Similar to MPI_Gather
  - The all prefix expresses that each process is a “root” of his neighborhood
- Also a vector “v” version for full flexibility

MPI_Neighbor_alltoall

```
MPI_Neighbor_alltoall(const void* sendbuf, int sendcount,
MPI_Datatype sendtype, void* recvbuf, int recvcount,
MPI_Datatype recvtype, MPI_Comm comm)
```

- Sends outdegree distinct messages
- Received indegree distinct messages
- Similar to MPI_Alltoall
  - Neighborhood specifies full communication relationship
- Vector and w versions for full flexibility

Nonblocking Neighborhood Collectives

```
MPI_Ineighbor_allgather(…, MPI_Request *req);
MPI_Ineighbor_alltoall(…, MPI_Request *req);
```

- Very similar to nonblocking collectives
- Collective invocation
- Matching in-order (no tags)
  - No wild tricks with neighborhoods! In order matching per communicator!

Topology Summary

- Topology functions allow users to specify application communication patterns/topology
  - Convenience functions (e.g., Cartesian)
  - Storing neighborhood relations (Graph)
- Enables topology mapping (reorder=1)
  - Not widely implemented yet
  - May requires manual data re-distribution (according to new rank order)
- MPI does not expose information about the network topology (would be very complex)

Neighborhood Collectives Summary

- Neighborhood collectives add communication functions to process topologies
  - Collective optimization potential!
- Allgather
  - One item to all neighbors
- Alltoall
  - Personalized item to each neighbor
- High optimization potential (similar to collective operations)
  - Interface encourages use of topology mapping!

Acknowledgments

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